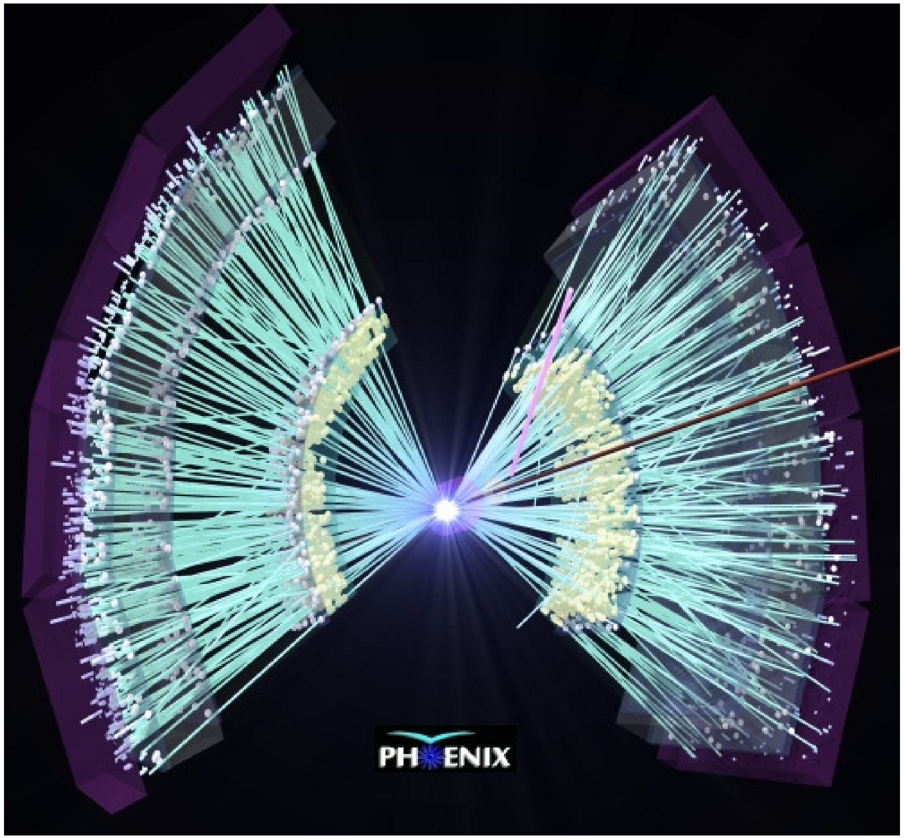
Relativistic Heavy Ions Collisions at PHENIX
(some of) Recent results



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Outline:

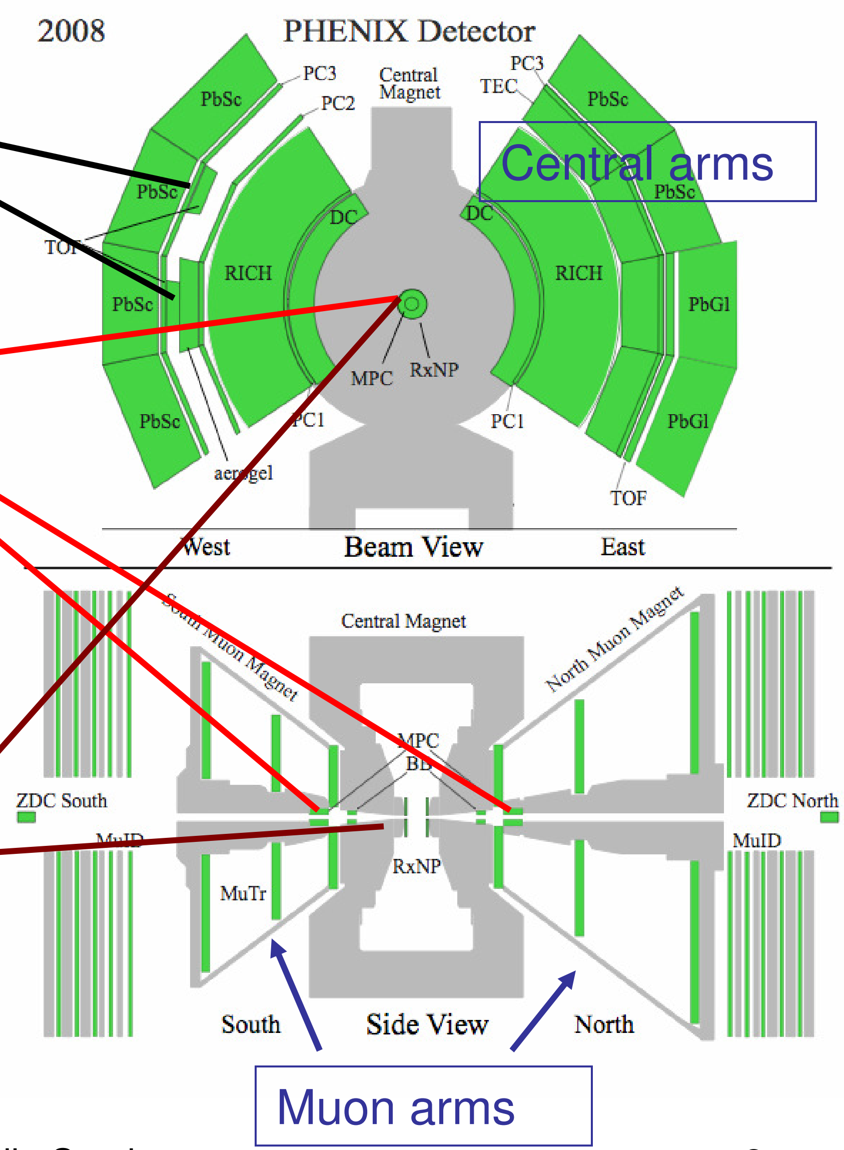
1. Jet quenching
2. Direct photons: high pT, thermal, correlations
3. J/Ψ, cold nuclear effects, suppression, v2
4. Heavy Flavor via non-photonic Electrons. Charm and Bottom
5. Two particle correlations, ridge, Mach cone
6. Anisotropic flow v_2 and v_4
7. Conclusions

PHENIX 2008. New detector sets

TOF-W: MultiGapResistive Plate chambers with strip readout, ~75ps time resolution, PID at high p_T

Muon Piston Calorimeter:
400 $PbWO_4$ crystals
Forward physics in pp
Reaction plane determination in AA
$3.1 < |\eta| < 3.7$

Reaction Plane Detector:
2 x 2 rings with 12 scintillator counters each.
Reaction plane determination in AA
Trigger counter for low energy runs
$\eta = 1.0 \rightarrow 1.5$, $\eta = 1.5 \rightarrow 2.8$



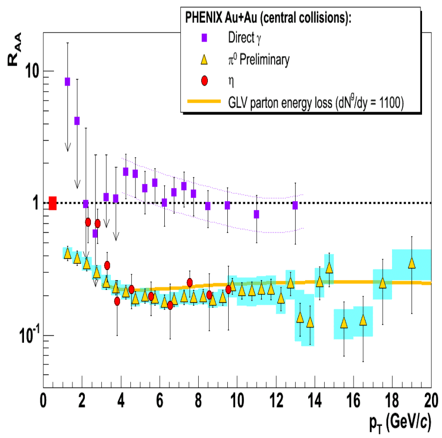
RHIC beam 2000-2008

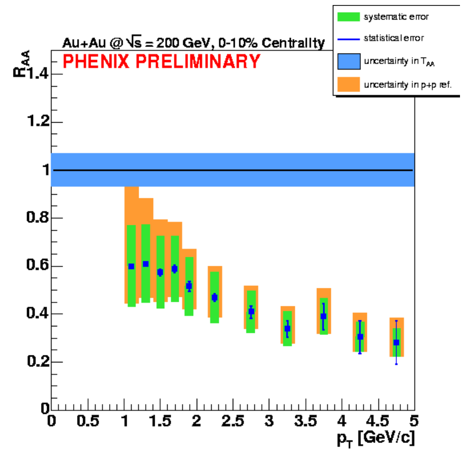
	p+p	d+Au	Au+Au	Cu+Cu
22.4 GeV				●
62.4 GeV	●		●	●
130 GeV			●	
200 GeV	●	●	●	●

Reference (p+p, d+Au) **sQGP ?** (Au+Au, Cu+Cu)

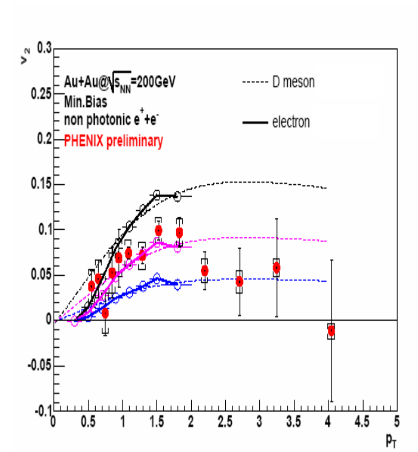
$h^{+/-}$, π^0, $\pi^{+/-}$, η, ω, p, K^0_s, Λ, e (from c & b)

sQGP @ RHIC

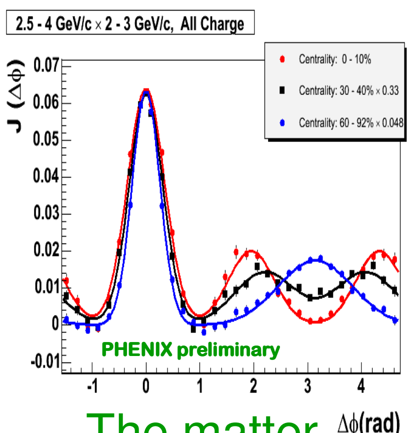




The matter is dense



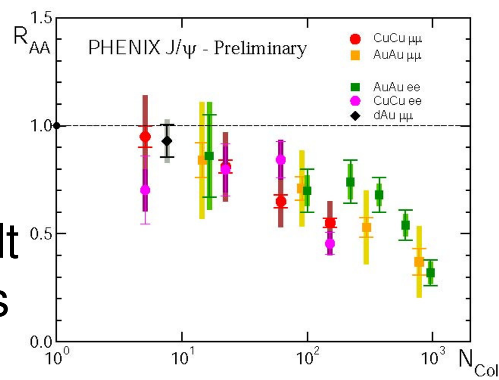
The matter is strongly coupled

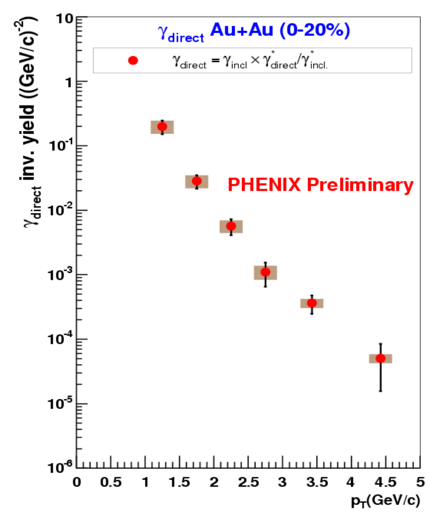


The matter modifies jets

strongly interacting
Quark-**G**luon
Plasma

The matter may melt but regenerate J/ψ's





The matter is hot

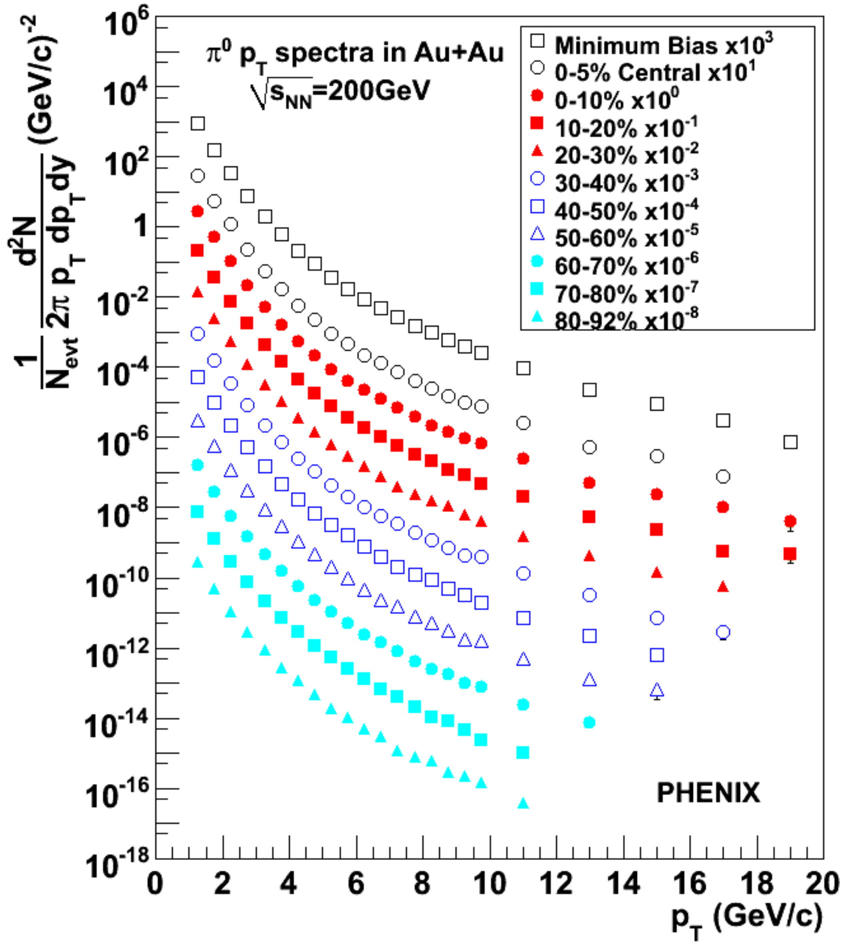
1. Jet quenching, Nuclear Modification Factor R_{AA}

New data:

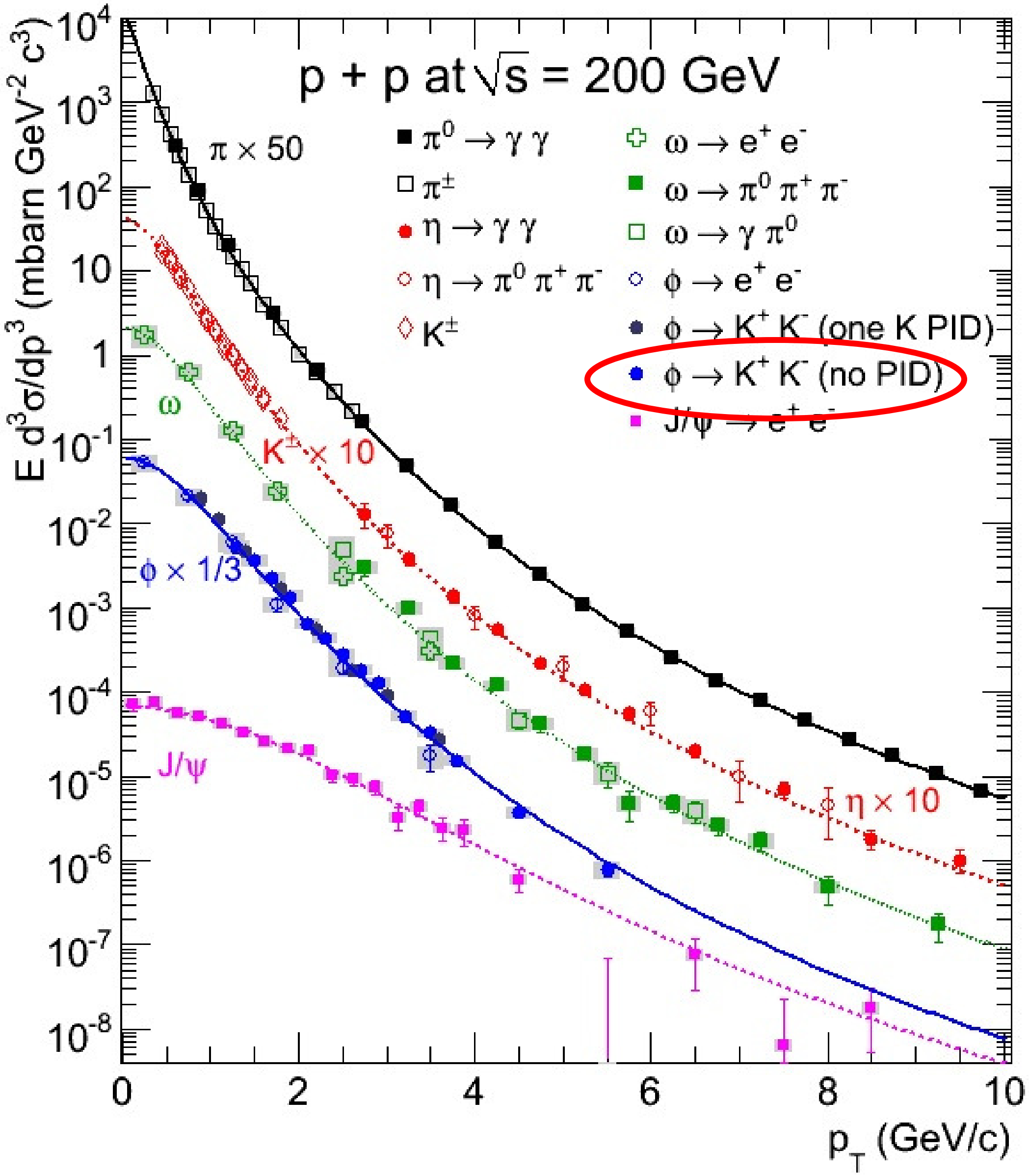
- Extended beam energy range down to 22 GeV
- Wider momentum range
- New particles
- Better statistics

More new data…

π^0 Au+Au 200 GeV (Run 4)

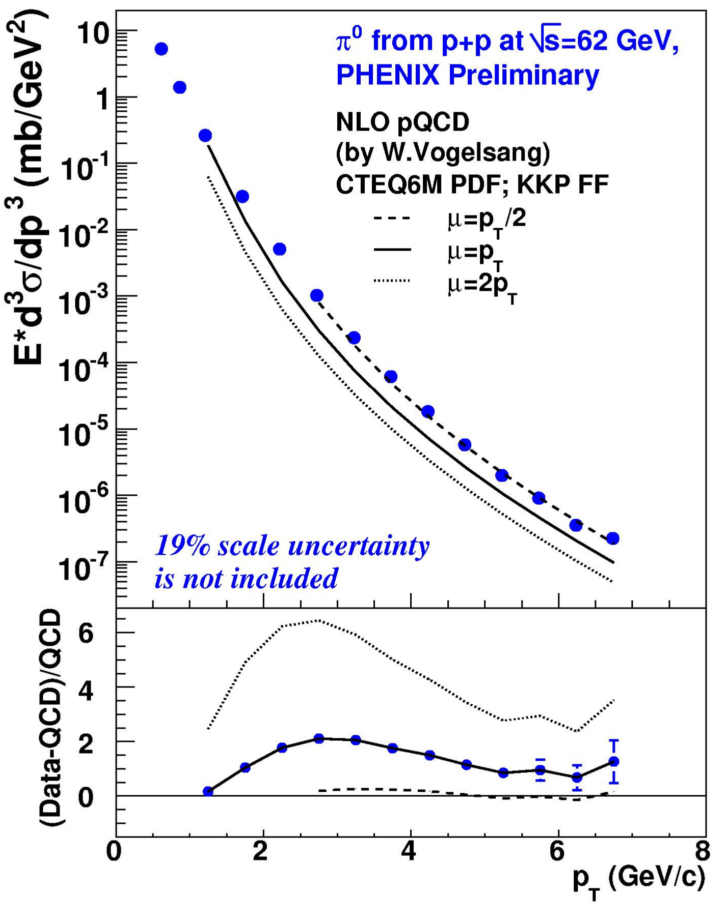


arXiv:0801.4020



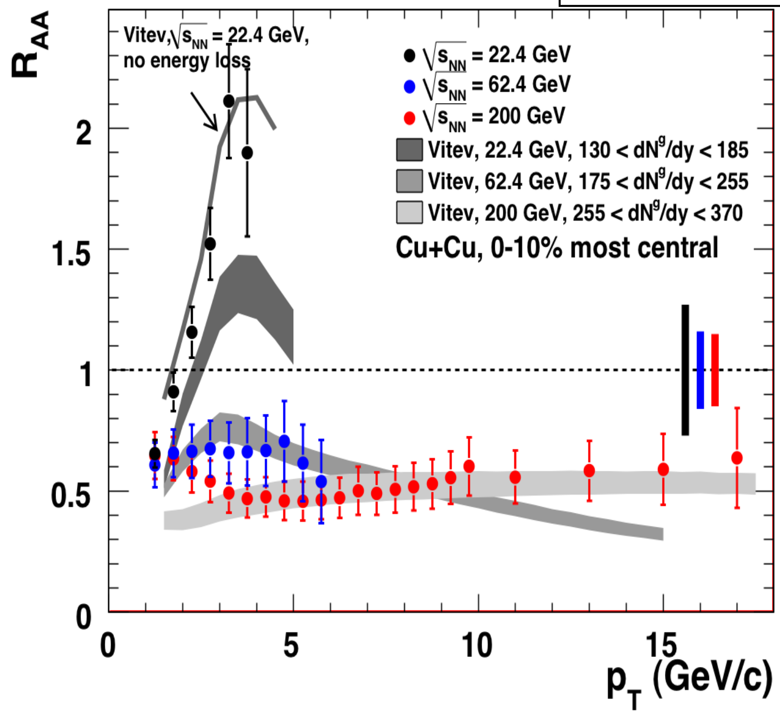
Beam energy scan

p+p reference at 62 GeV



π^0 Cu+Cu **22,62,200** GeV (Run 5)

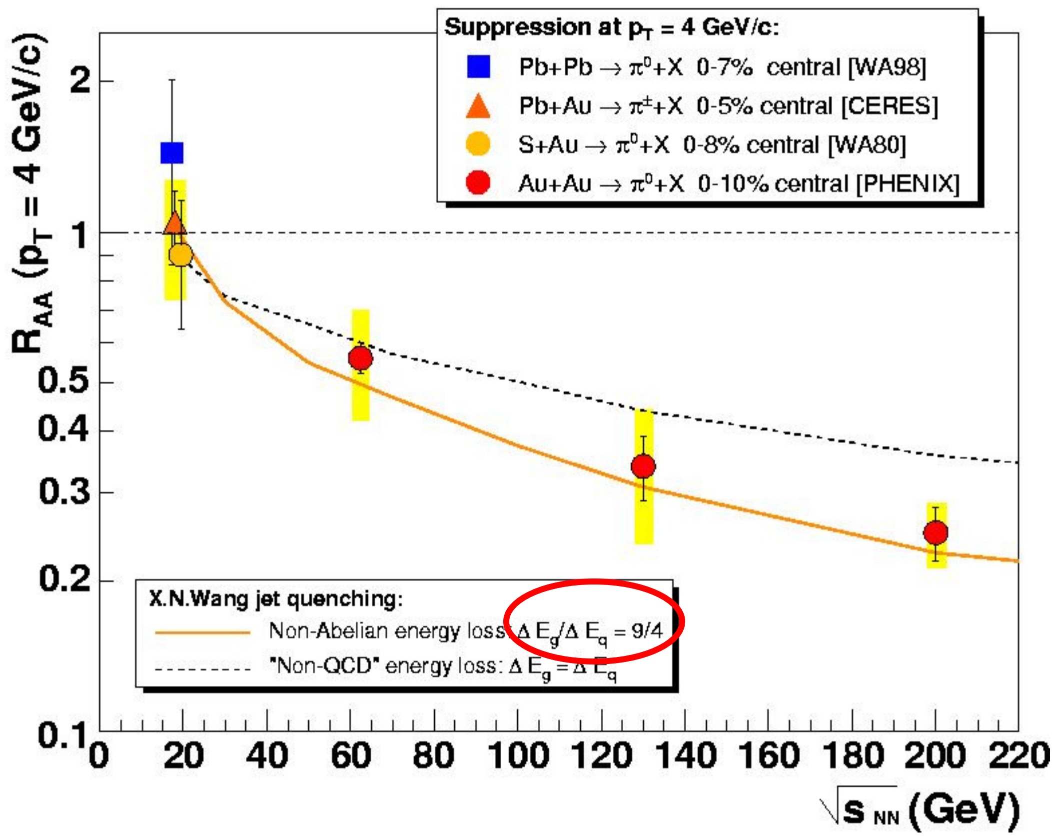
arXiv:0801.4555



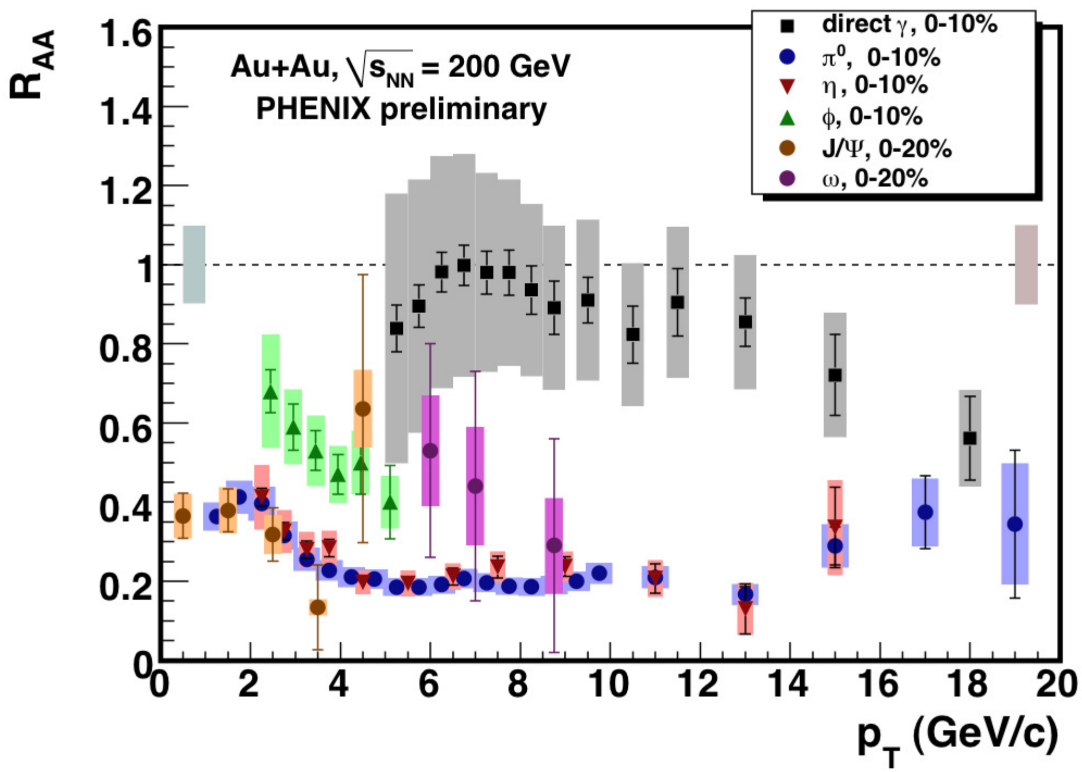
Suppression is not seen at low energy.

Model calculations indicate quenching expected at $\sqrt{s_{NN}}$ = 22 GeV, but Cronin effect dominates ?

Suppression increases with beam energy

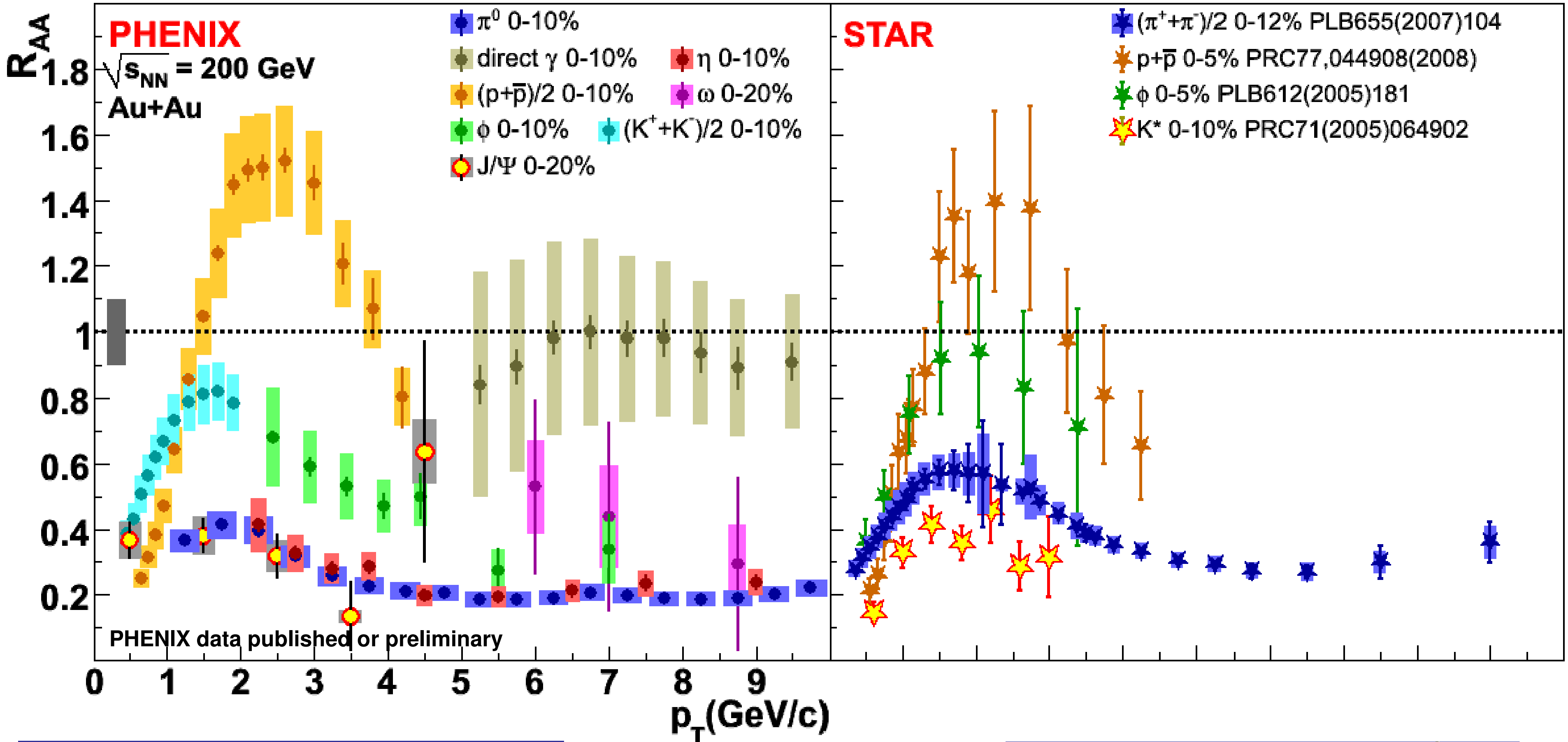


Dependence on Particle Species: p^0, h, f, J/ψ, ω Mesons and Direct γ in Au+Au at 200 GeV



- Same suppression pattern for π^0 and η: Consistent with parton energy loss and fragmentation in the vacuum
- R_{AA} for φ's larger than π^0 R_{AA} for $2 < p_T < 5$ GeV/c

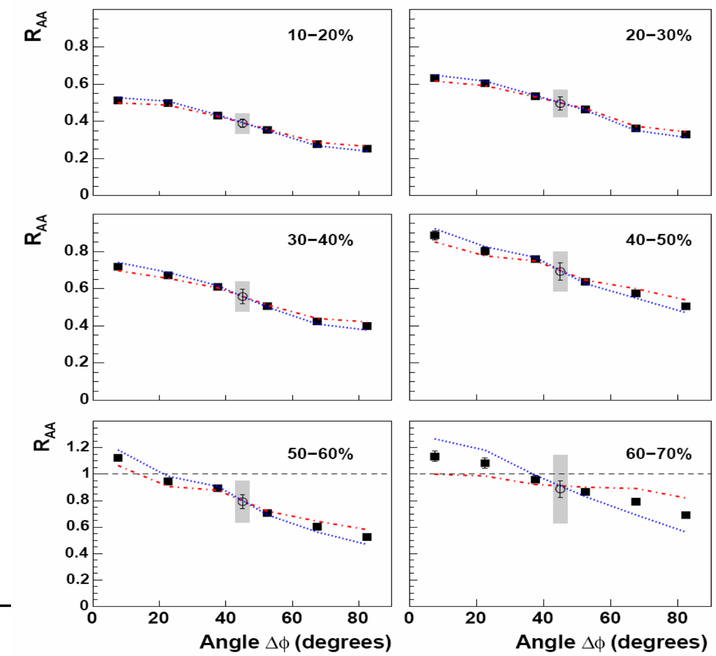
Mass ordering brakes?



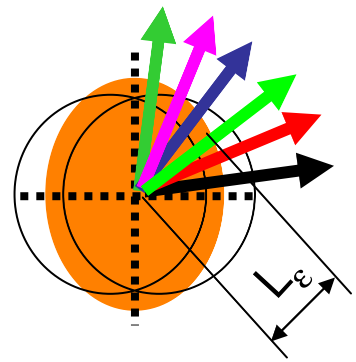
π^0&$\pi^\pm$ are suppressed by ~4-5
γ's hold the N_{coll} scaling
η falls dead on π^0
Baryons are enhanced including strange (not shown).

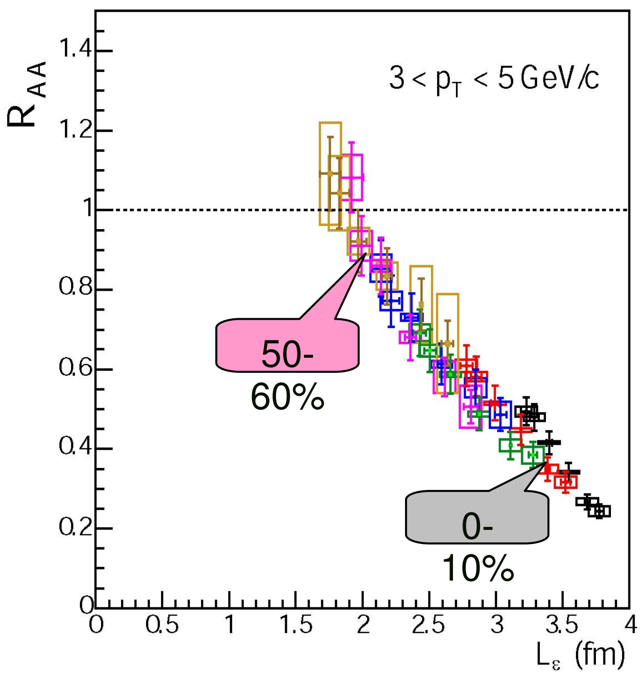
ω is suppressed (inconclusive)
φ behaves differently. Why?
$K^\pm$ is at low p_T, no overlap.
K* behaves like π^0?
J/Ψ looks like K*… ?

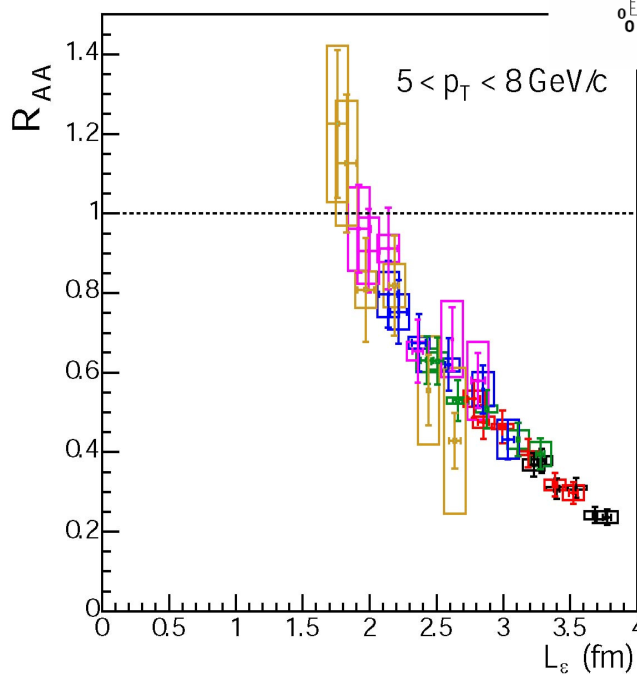
New type of data for π^0 RAA vs. reaction plane orientation



Changing amount of matter by centrality and by angle versus the reaction plane







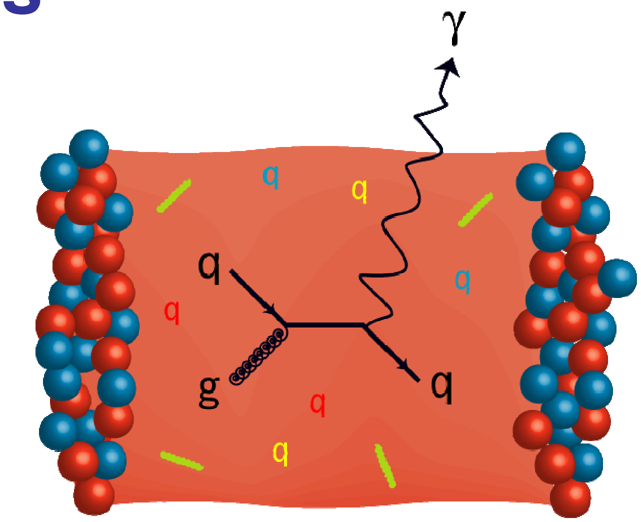
Thickness, L_ε

Absence of suppression in layer less than 2 fm

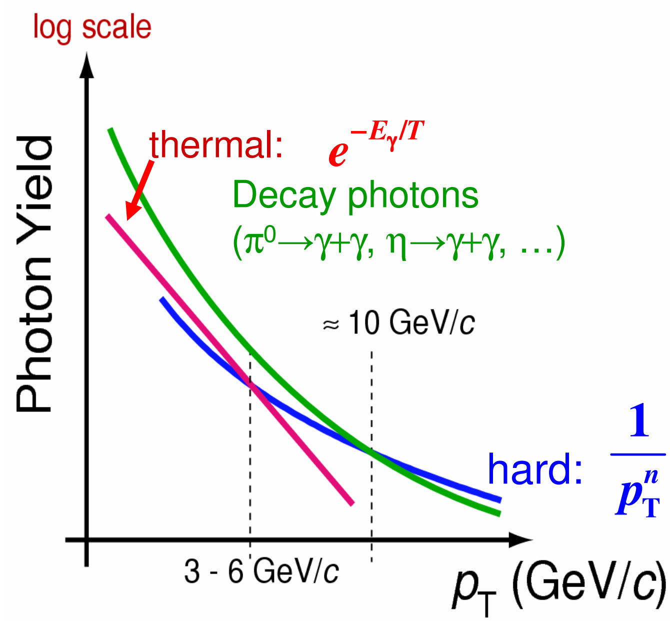
Formation time effect?

2. Direct photons

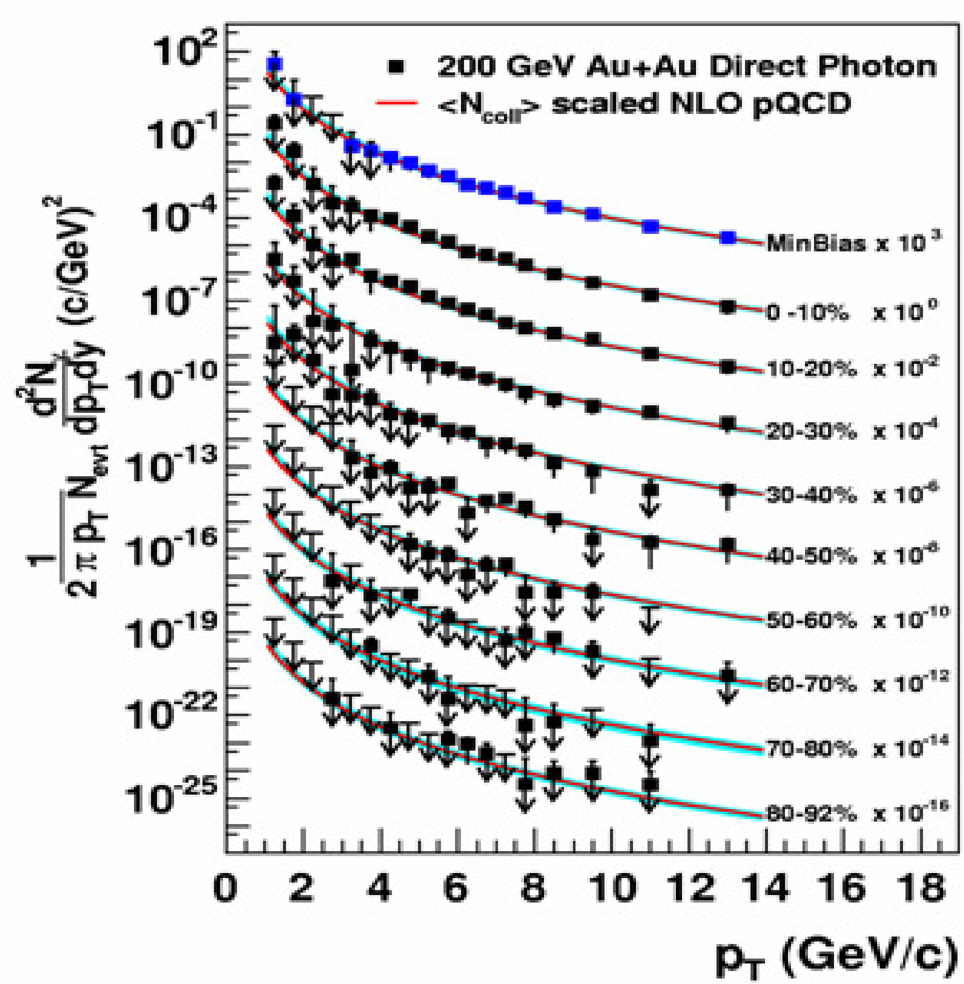
- Direct photons are an important probe to investigate the characteristics of evolution of the matter created by heavy ion collisions.
  - Penetrate the strong interacting matter
  - Emitted from every stage of collisions
    - Hard photons (**High pT**)
      – Initial hard scattering, Pre-equilibrium
    - Thermal photons (**Low pT**)
      – Carry the thermodynamic information from QGP and hadron gas



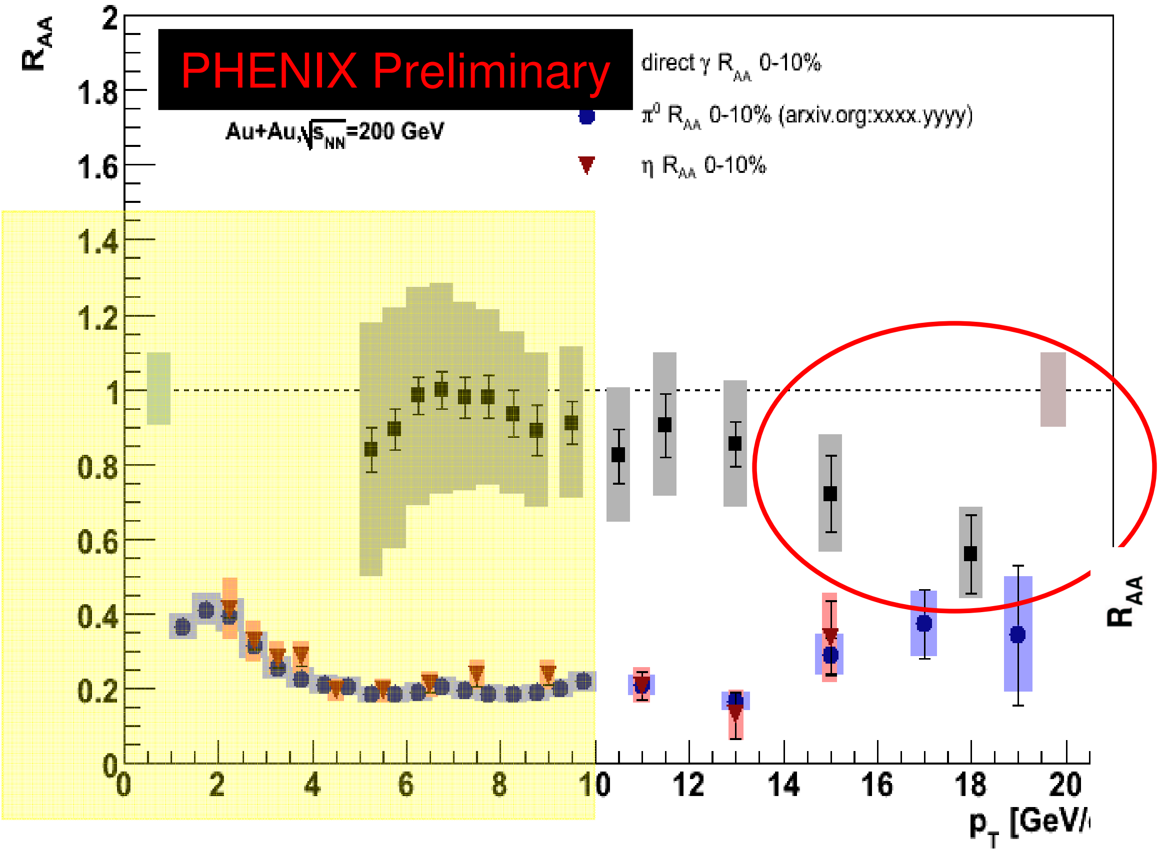
Central Au+Au at RHIC



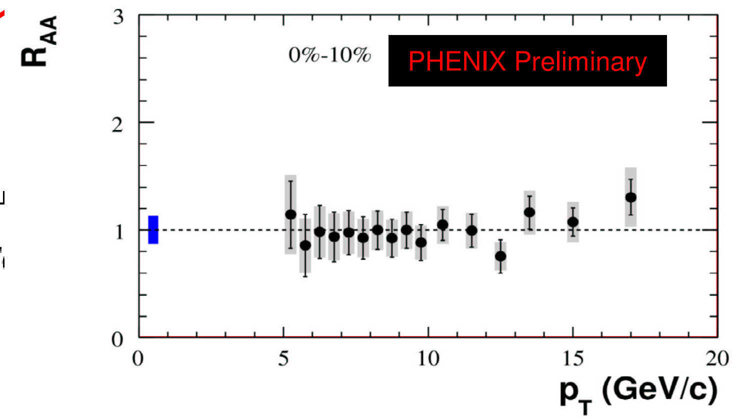
High Pt photons spectrum Au+Au



Check of NN-binary scaling

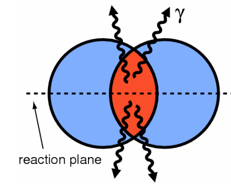


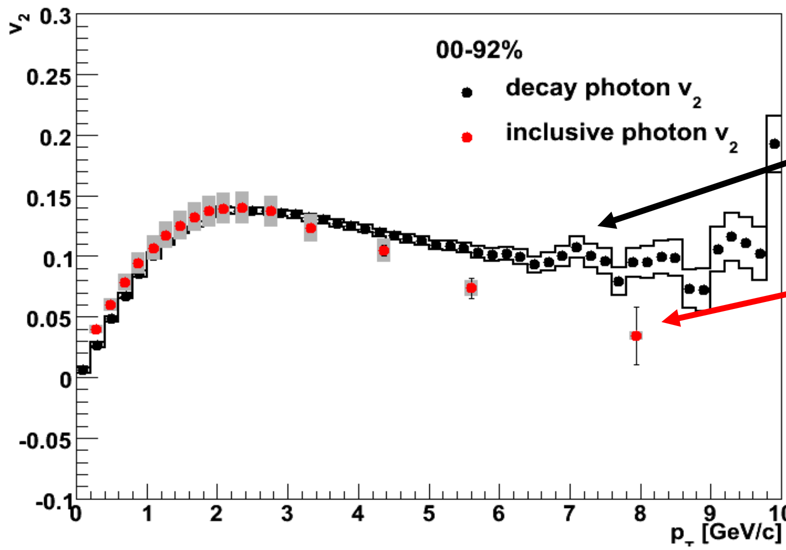
But,
Central Cu+Cu 200 Ge,V
Direct Photons



- Run 4 (QM06): High p_T γ suppression?
- Isospin (charge) effect ? ← Data for p+p were used as a reference. Over normalized? Need p+n and n+n ! (d+Au, last year Run8!)

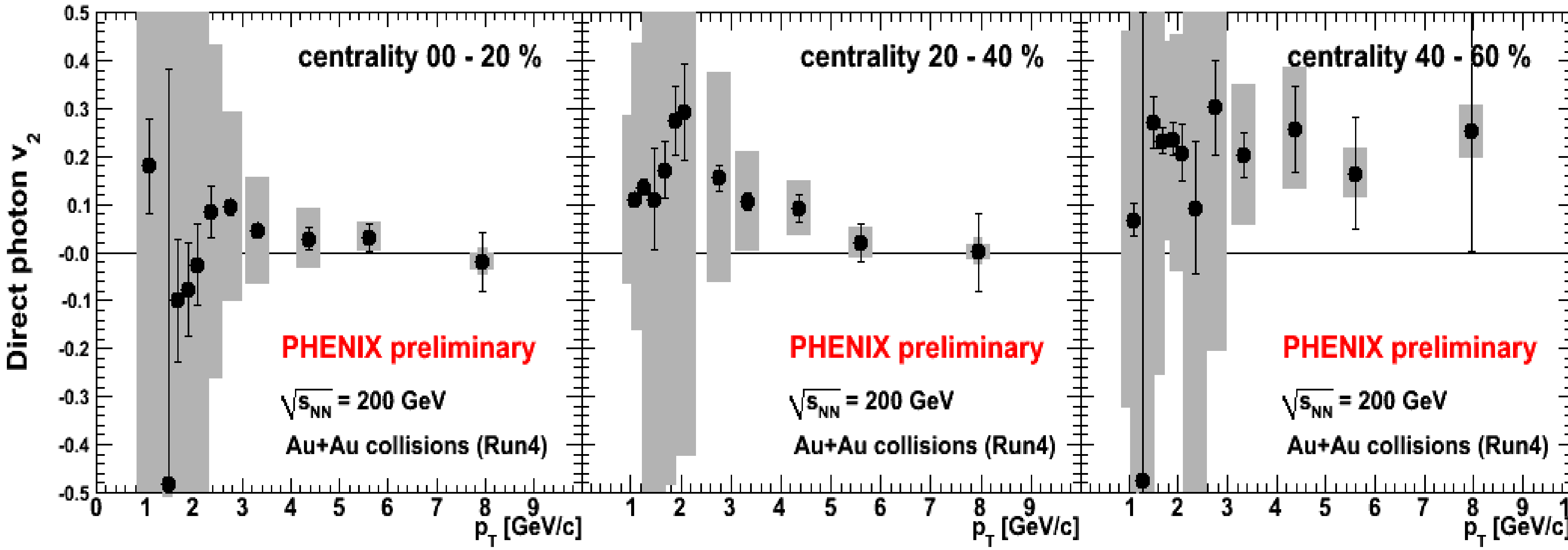
Direct γ v_2 : Au+Au 200 GeV





Estimate from all hadron decays

All photons measured



Low pT Photons

Long-awaited results for both p+p and Au+Au

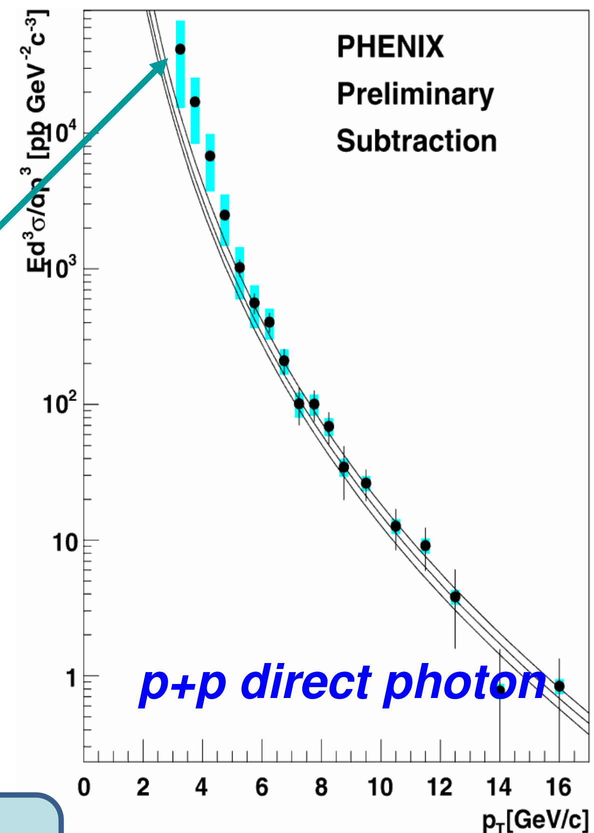
- Experimental determination is very important since applicability of pQCD is doubtable in low pT region.

In 'real' photon measurement

- Measured yield with a large systematic error

Difficulty on measuring low pT "real" direct photons

1. Finite energy resolution of the EMCal
2. Large hadron background

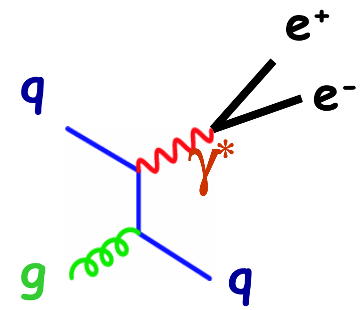


Alternative method to measure low pT direct photons
→ Measure e^+e^- pairs from 'virtual' direct photons

New method: to use di-electrons from internal conversion

Direct photon production process, like gluon Compton scattering
$q+g \rightarrow q+\gamma$,

has an associated process through internal conversion
$q+g \rightarrow q+\gamma^* \rightarrow q+e^+e^-$



Kroll-Wada formula, symbolic representation

$d^2n / dm_{ee} = F_{QED}(m_{ee}) * S * dn_{\gamma}$

factor F_{QED} – can be calculated in QED,

$S = 1$ for $P_{ee} >> m_{ee}$

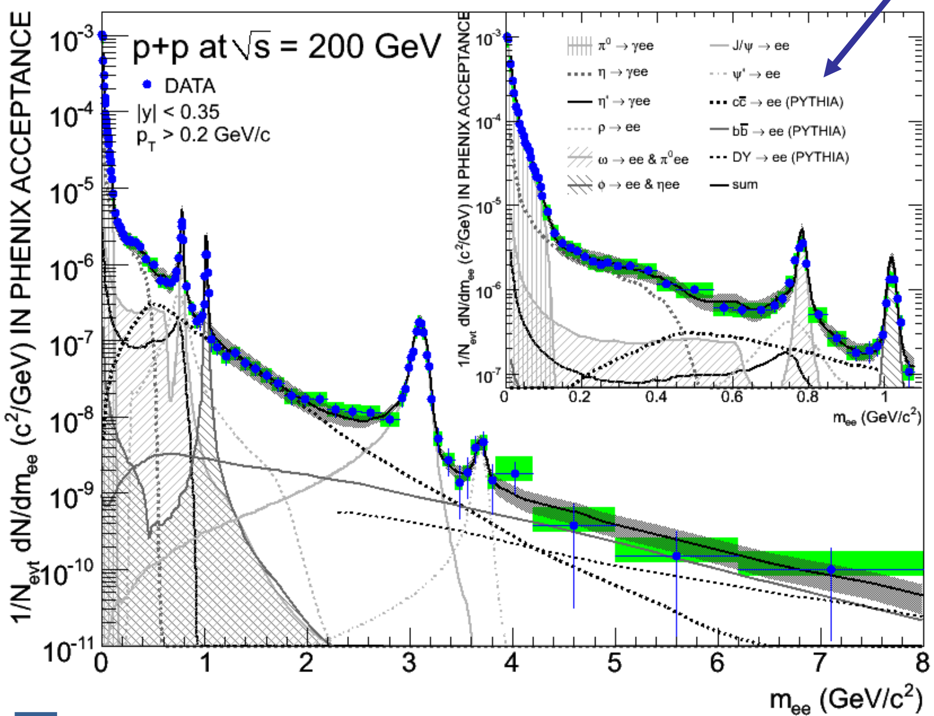
arXiv:0804.4168

Formula works also for meson Dalitz decays and factor S is related to meson form factor

Di-electron spectrum. “Cocktail” comparison

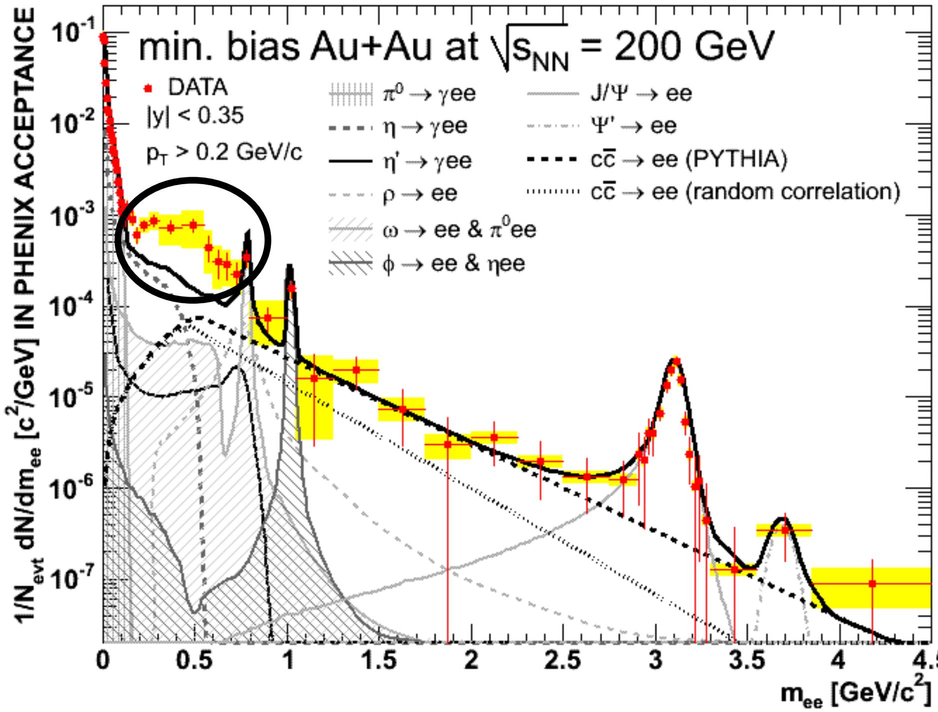
arXiv: 0802.0050

p+p



Au+Au

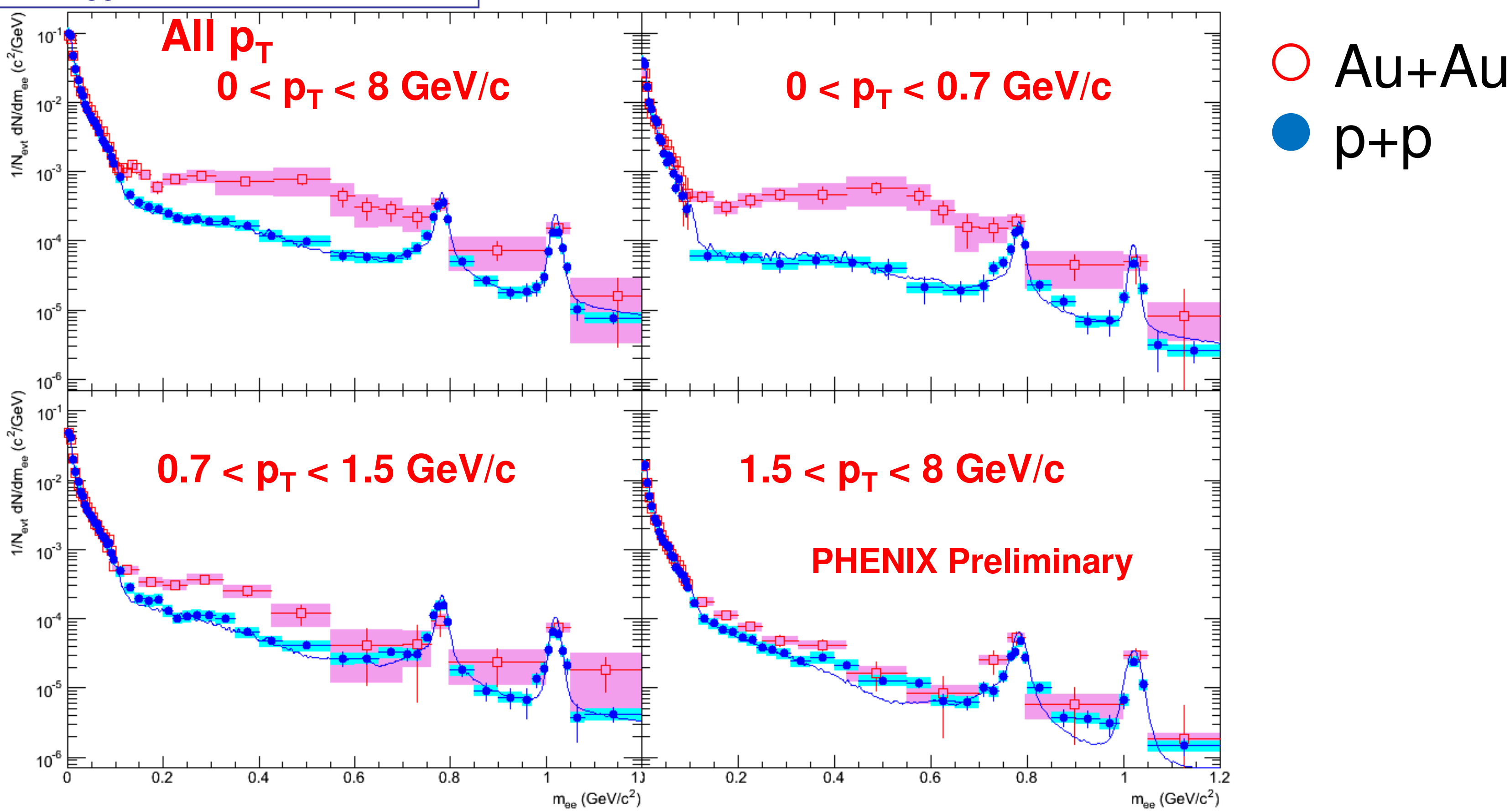
arXiv: 0706.3034



- p+p
  - Excellent agreement with cocktail
- Au+Au
  - Large enhancement in low mass region
  - Integrated yield in150MeV < m_{ee} < 750MeV
    - Real/cocktail = 3.4 ± 0.2(stat) ± 1.3(sys) ± 0.7(model)

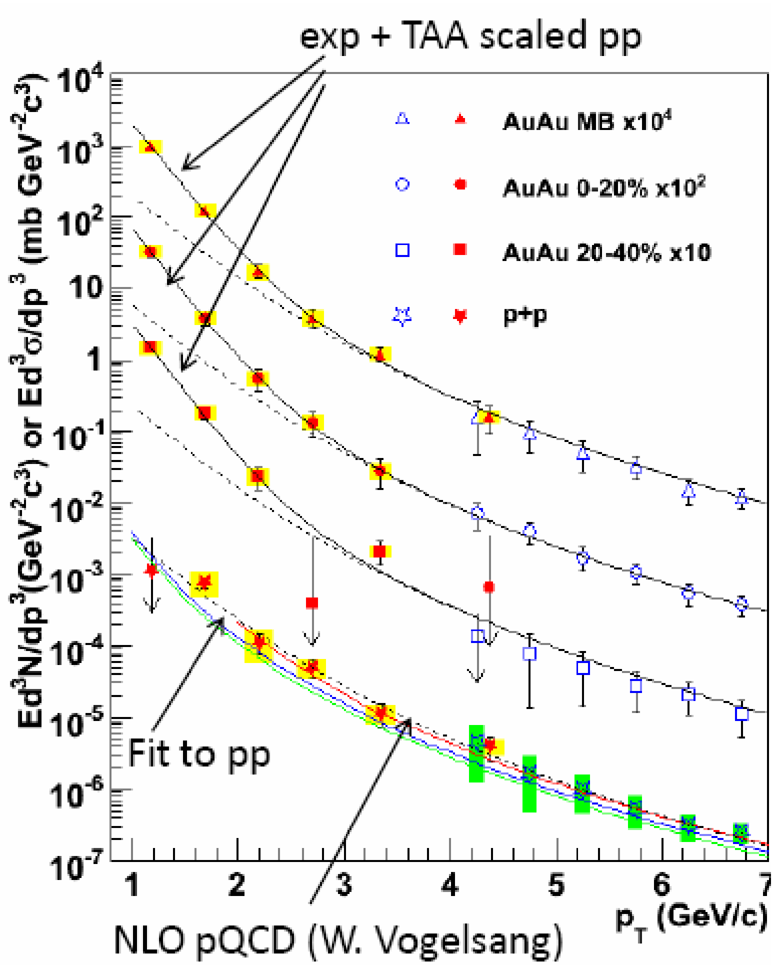
m_{ee} , p_T Sliced Mass Spectra

Normalized by the yield in m_{ee} < 100MeV



- Shape differences between p+p and Au+Au are larger at lower pT.

Thermal Photon Spectra via internat conversion



The virtual direct photon fraction is converted to the direct photon yield.

p+p

- First measurement in 1-4GeV/c
- Consistent with NLO pQCD

→ **Serves as a crucial reference**

Au+Au

- Above binary scaled NLO pQCD

→ **Excess comes from thermal photons?**

TABLE I: Summary of the fits. The first and second errors are statistical and systematical, respectively.

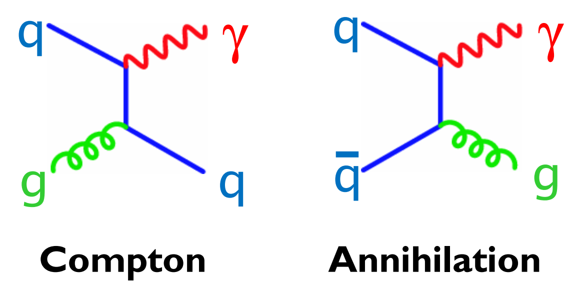
centrality	$dN/dy(p_T > 1\mathrm{GeV}/c)$	T(MeV)	χ^2/DOF
0-20%	$1.10 \pm 0.20 \pm 0.30$	$221 \pm 23 \pm 18$	3.6/4
20-40%	$0.52 \pm 0.08 \pm 0.14$	$215 \pm 20 \pm 15$	5.2/3
MB	$0.33 \pm 0.04 \pm 0.09$	$224 \pm 16 \pm 19$	0.9/4

Mean photon temperature in collision

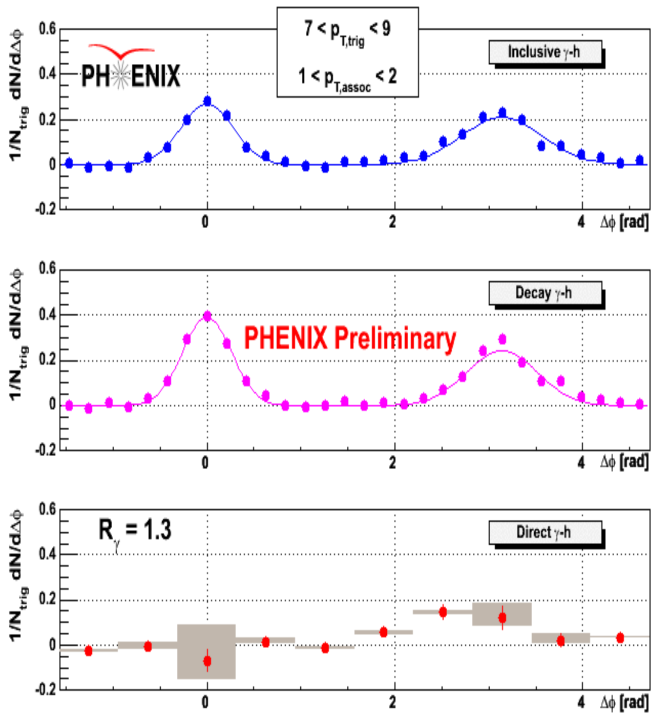
arXiv:0804.4168

Two-particle Direct Photon-Jet ϕ Correlation Measurements

- Excellent Complement to *h-h* di-jet
- "Leading Order" Picture
  - Exact Momentum Balance w/ Away-Side Jet
  - Compton Dominance (h-h)
- p+p: Measure Gluon Distribution Function
- A+A:
  - Calibrated Probe of Energy Loss
  - More sensitive (?) probe than single particle spectra or Di-Hadron Correlations
  - Like having one of your jets automatically reconstructed!

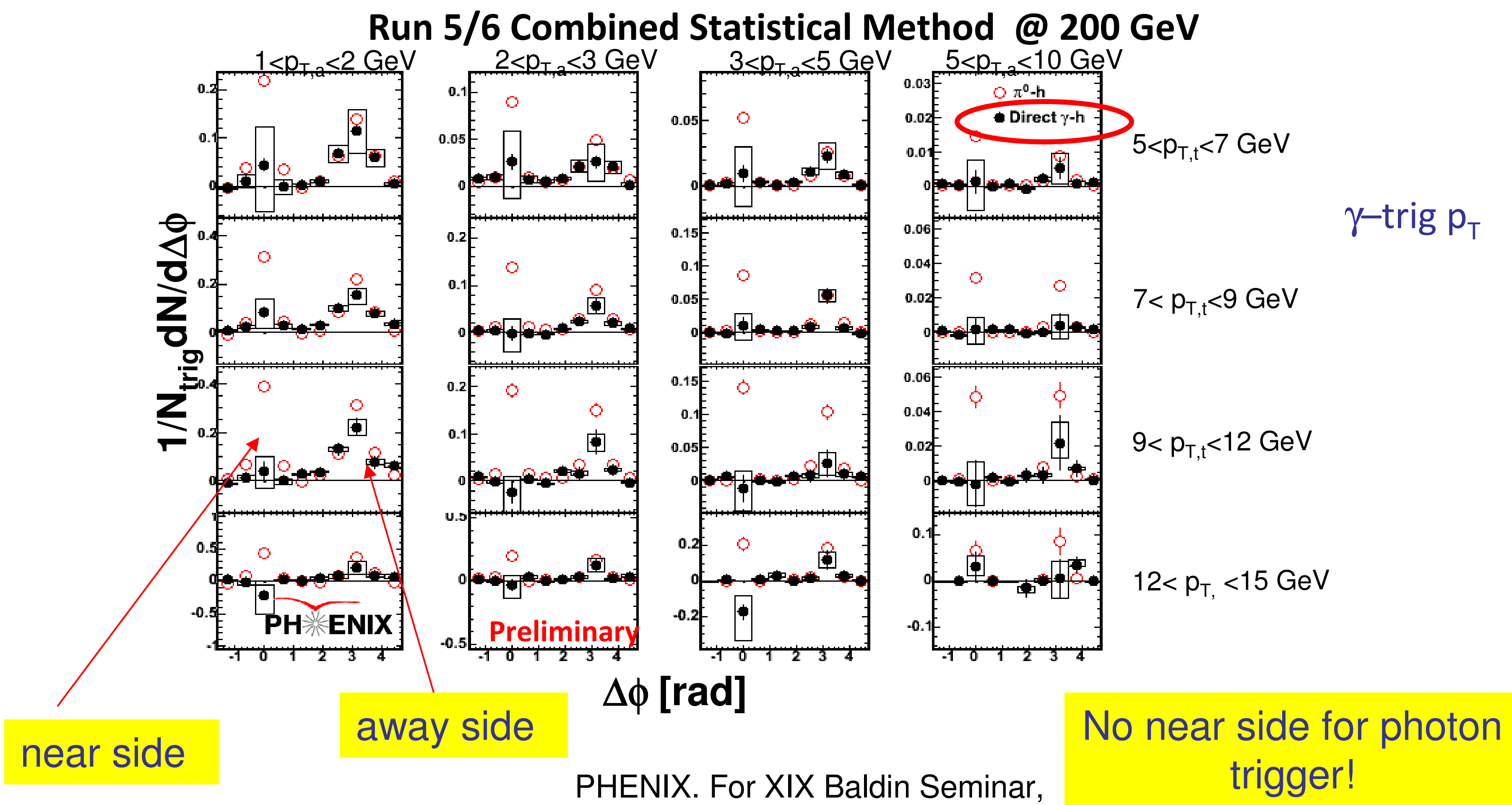


Direct Photon Processes at LO



It works nicely… (new p+p results)

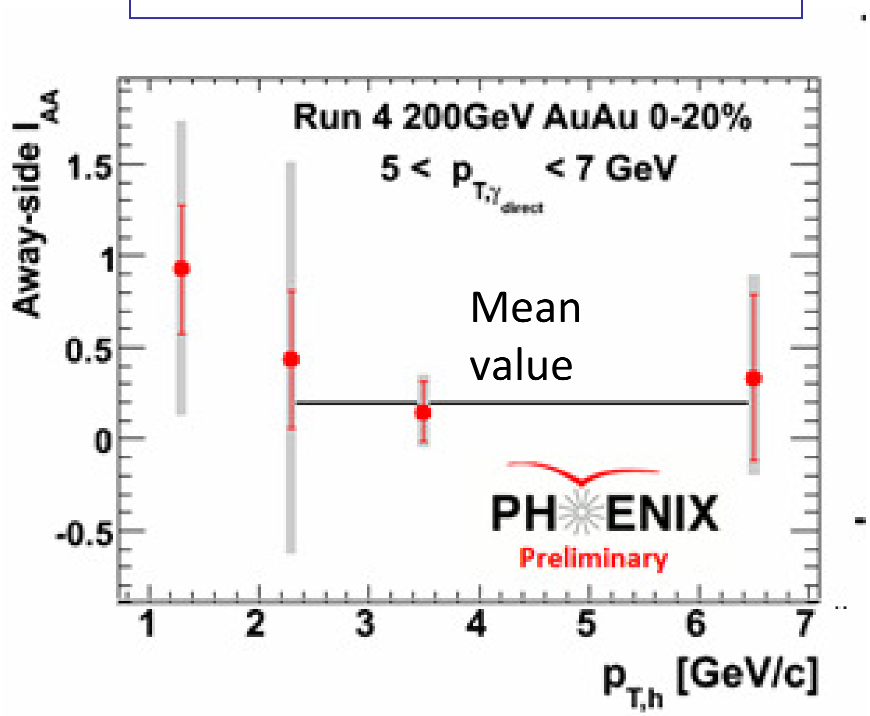
- Over a wide range of pt bins, clear Compton awayside-dominant signature
- New PHENIX highest precision p+p dataset



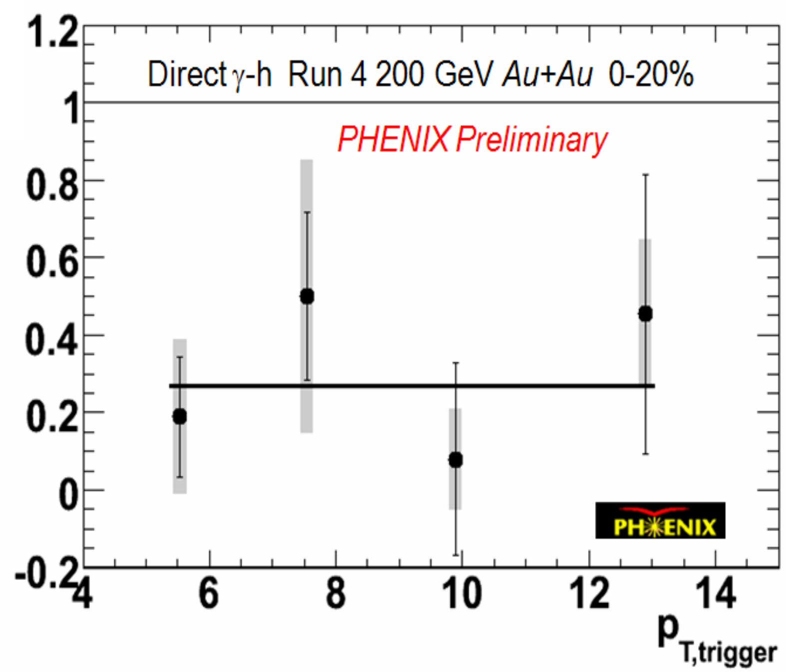
PHENIX. For XIX Baldin Seminar, Dubna 2008

Direct γ trigger: Au+Au away-side suppression, I_{AA}

Scan on hadron momentum



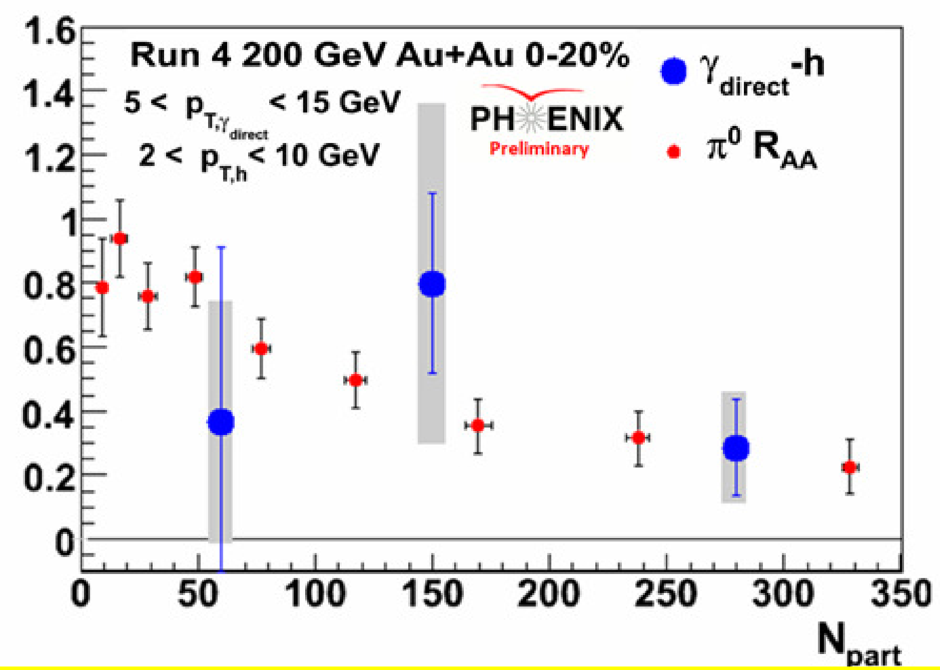
Scan on tigger momentum



Mean Value I_{AA} (away side) vs Centrality

Mean Value $I_{AA}(p_{Ta}, p_{T\gamma})$ →

$$\frac{1}{\Delta p_T^{assoc}\,\Delta p_T^{\gamma\,trig}}\int I_{AA}(p_T^{assoc}, p_T^{\gamma\,trig})\,dp_T$$

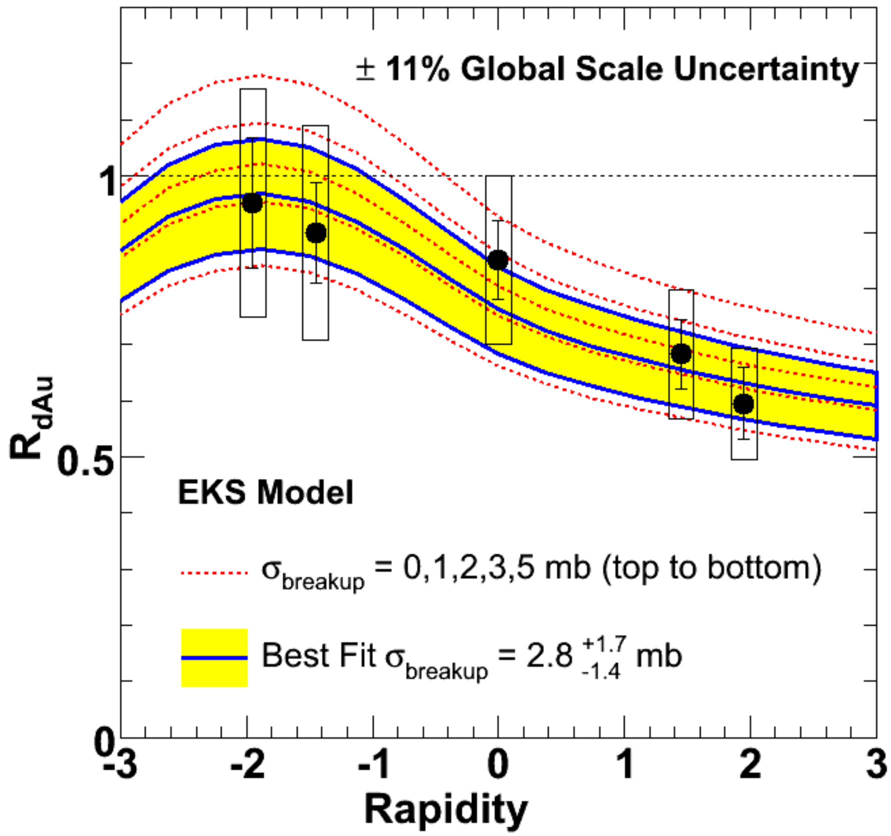


- I_{AA} ~= R_{AA} → surface bias paradigm (still with large uncertainties)
- First look @ Run7 statistical improvements look encouraging

3. J/Ψ

J/ψ d+Au: Cold Nuclear Matter effects

J/ψ R_{dAu} 200 GeV



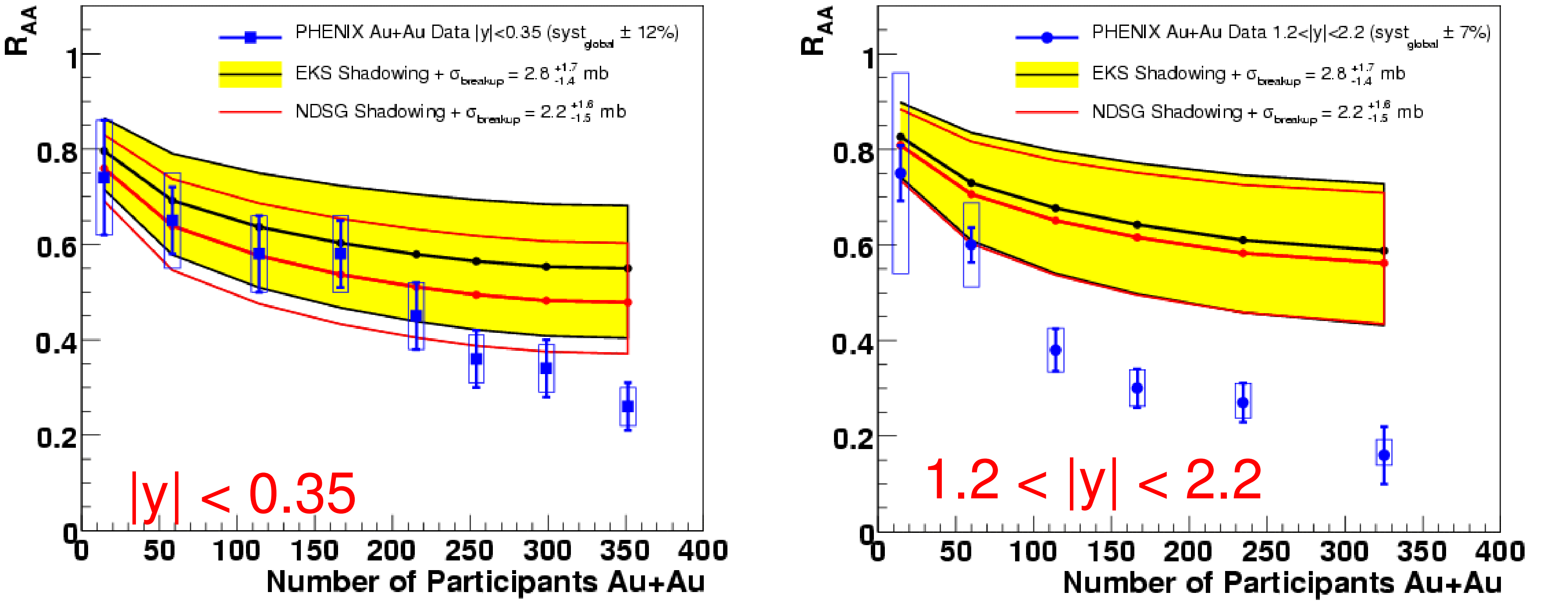
- Increased Run 5 p+p statistics (x10 Run 3)
- Improved & consistent p+p and dAu analysis
  - Improved alignment, resolution, yield extraction,…
  - Cancellation of systematic errors in R_{dAu}
- Result: CNM = Shadowing(EKS) + $\sigma_{Breakup}$ = 2.8 mb
  - Consistent within errors with previous results
  - and with $\sigma_{Breakup}$=4.2+/-0.5mb (SPS result)

arXiv:0711.3917

Run8 d+Au ~30 times larger statistics is coming

J/ψ suppression in Au+Au: include CNM Effects

J/ψ R_{AuAu} 200 GeV (Run4)

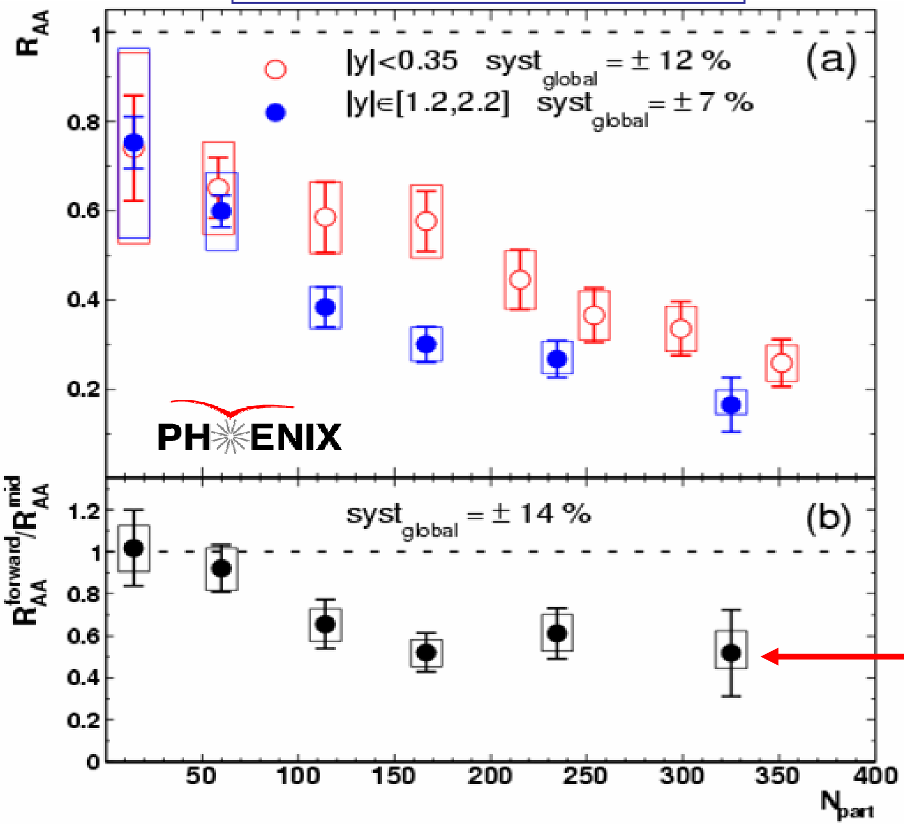


arXiv:0711.3917

- Large errors still (need Run 8 d+Au, Run 7 Au+Au)
  - Comparison suggests more forward suppression beyond CNM than at mid-rapidity
  - BUT models shown don't describe R_{dAu} impact parameter dependence

More look on rapidity dependence

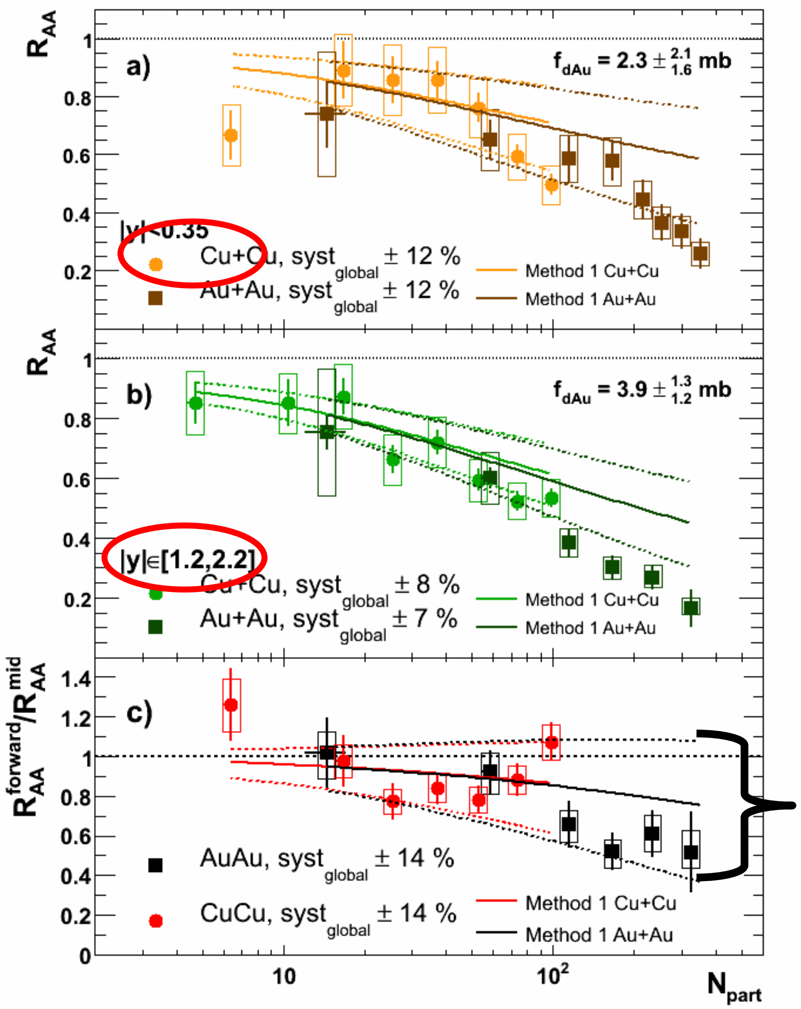
Au+Au 200 GeV



At forward rapidity y=[1.2, 2.2] absorption 2 times stronger than in central region with high energy dencity.
Recombination of cc-bar pairs?

J/ψ R_{AA} Cu+Cu and Au+Au

J/ψ R_{AA} 200 GeV

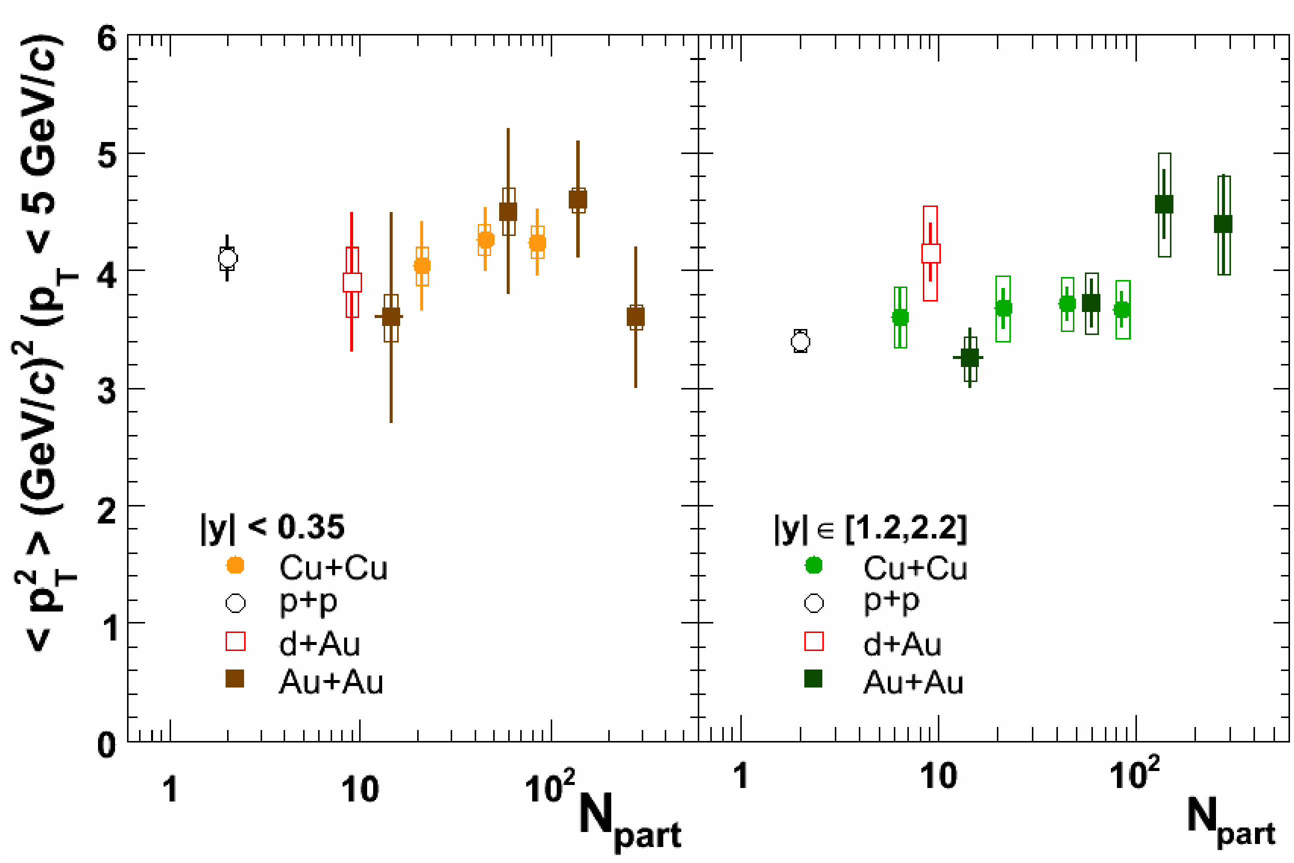


arXiv:0801.0220

- Approx 2x more J/ψ statistics in Cu+Cu sample than Au+Au sample
  - More precise N_{part}<100 info
- Curves show R_{AA} prediction from ad hoc CNM fit to R_{dAu} separately at y=0 and y > 1.2
- CNM from R_{dAu} fit describes suppression for N_{part} < 100.

R_{dAu} constraints are **not sufficient** to say if suppression beyond cold nuclear matter is stronger at forward rapidity

J/ψ $<p_T^2>$ Cu+Cu and Au+Au



arXiv:0801.0220

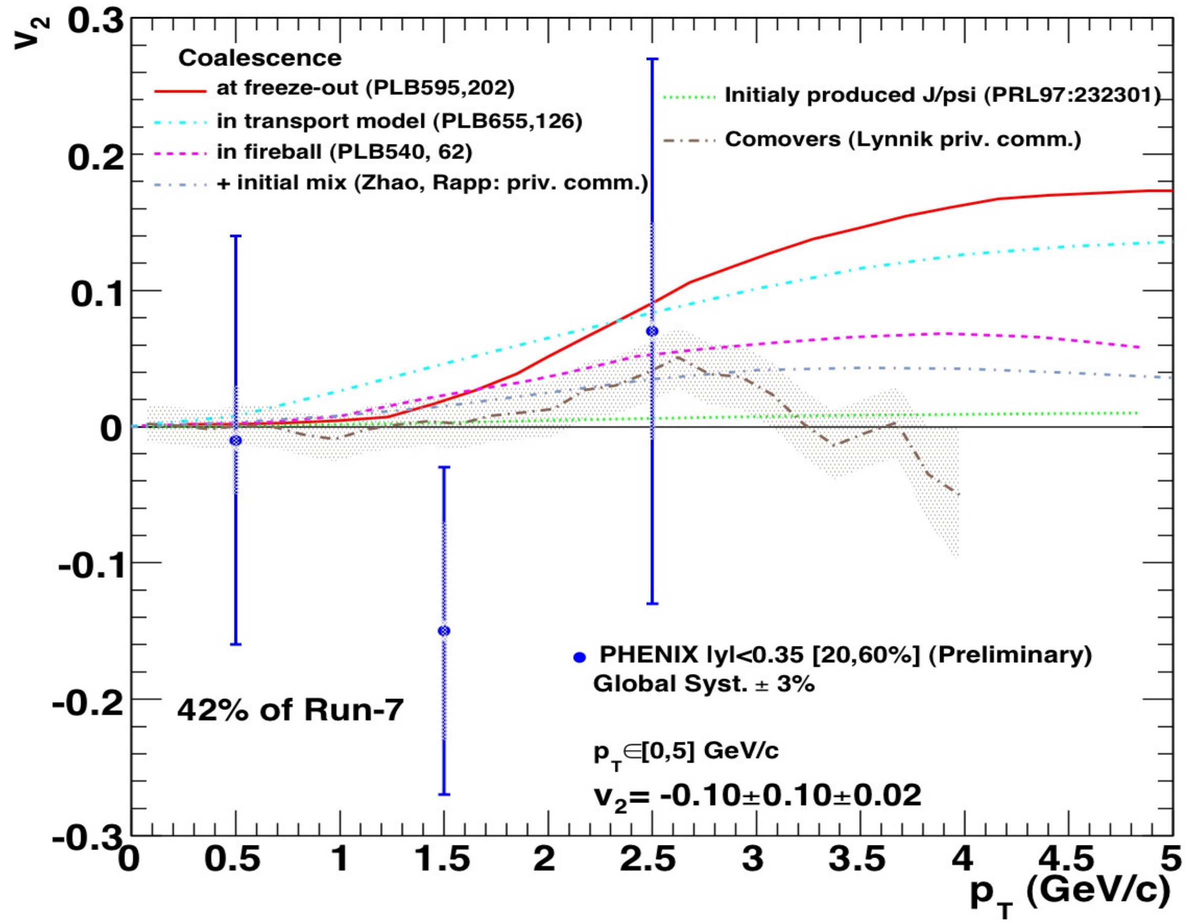
- No (or modest) p_T broadening of J/ψ
  - Conspiracy of low p_T suppression and recombination?

Azimuthal assimetry for - J/Ψ → e^+e^- at midrapidity

First ever at RHIC.

v_2 - J/Ψ →$\mu^+\mu^-$ coming soon

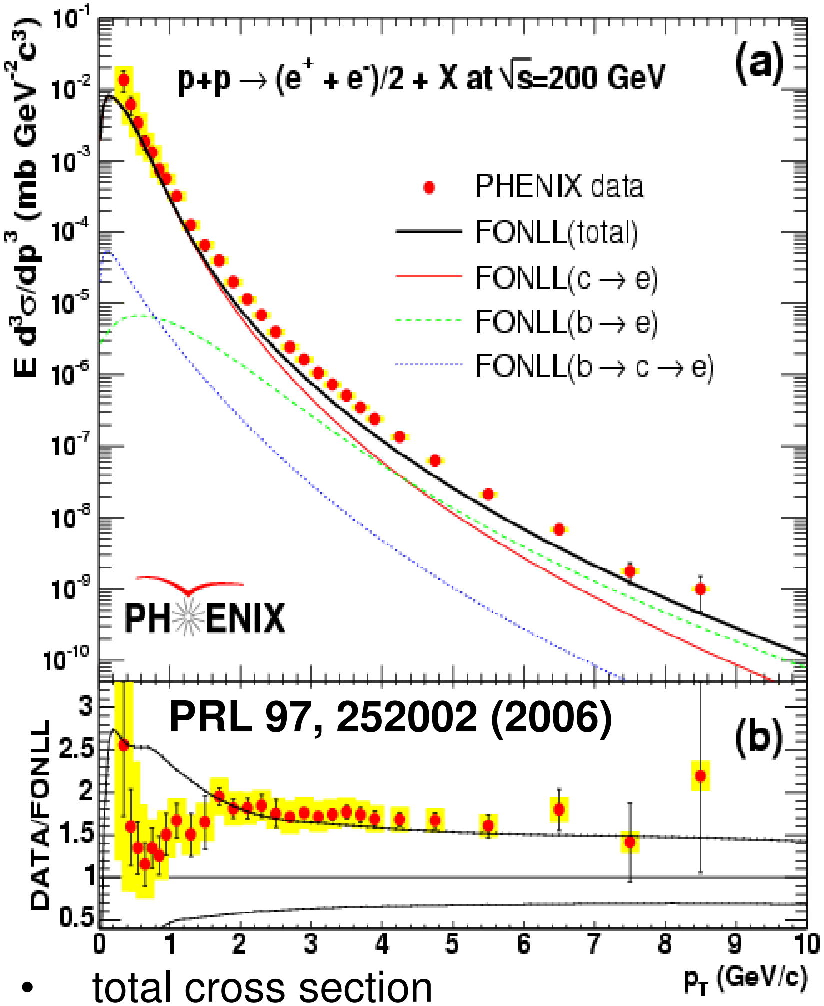
J/Psi coalescence ?

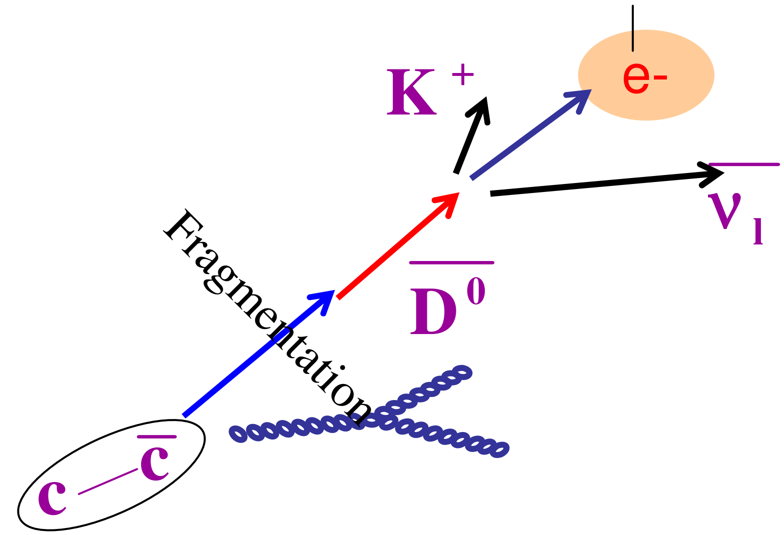


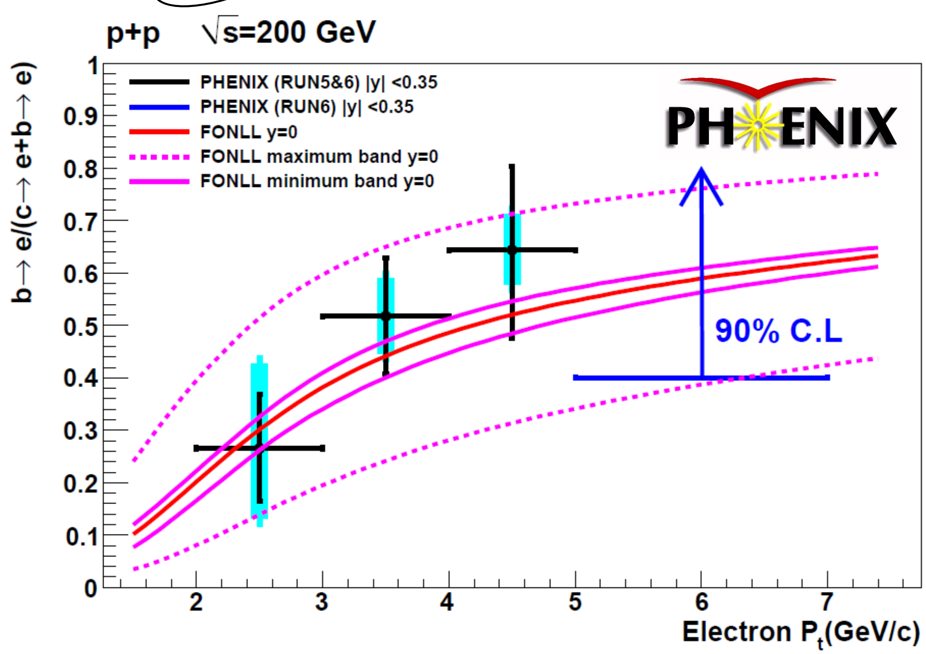
In process, less than half the dataset, muons will help, no clear model predictions

4. Heavy Flavor via non-photonic electrons

Heavy flavor (c+b): p+p at √s = 200 GeV. Good reference



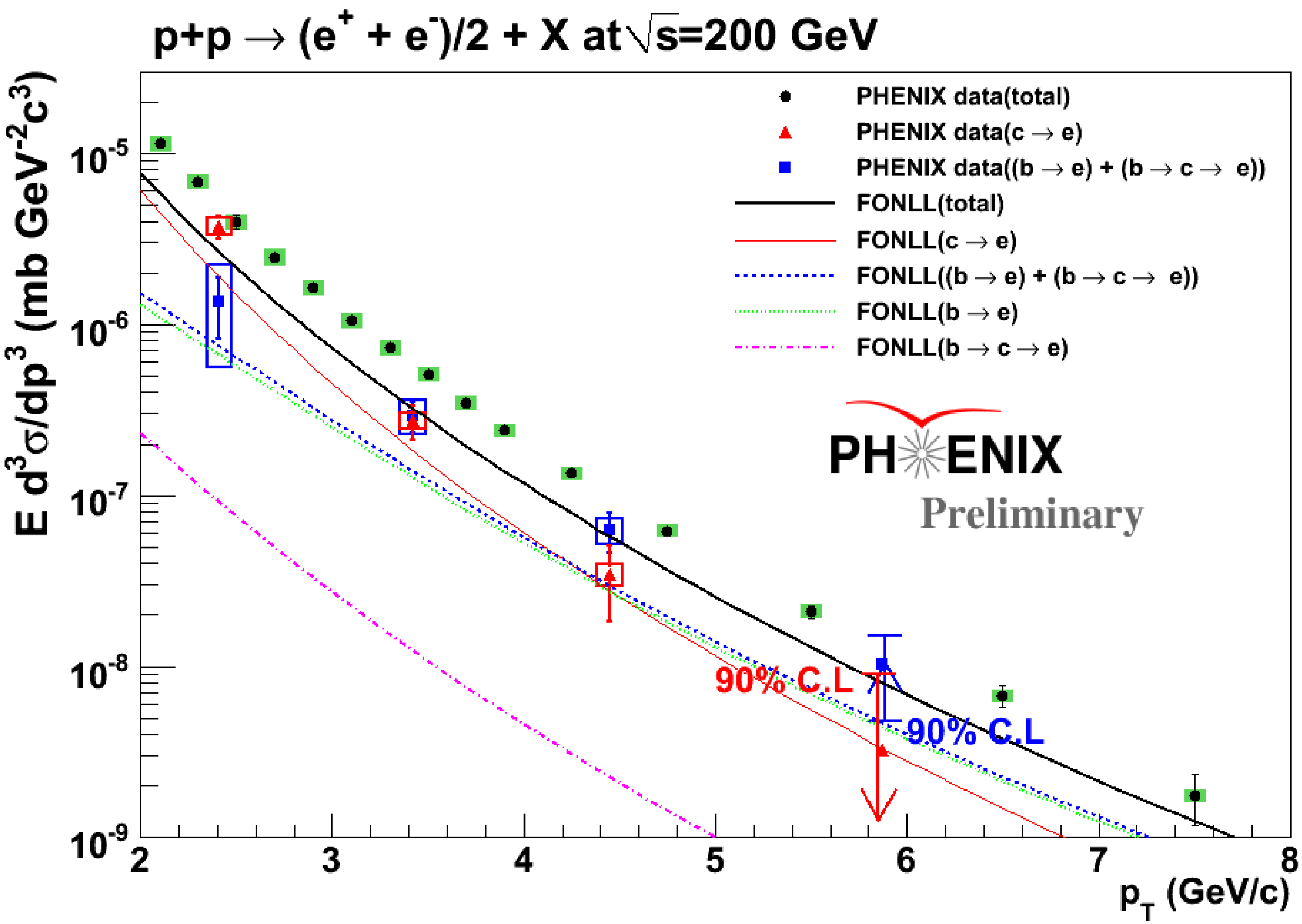




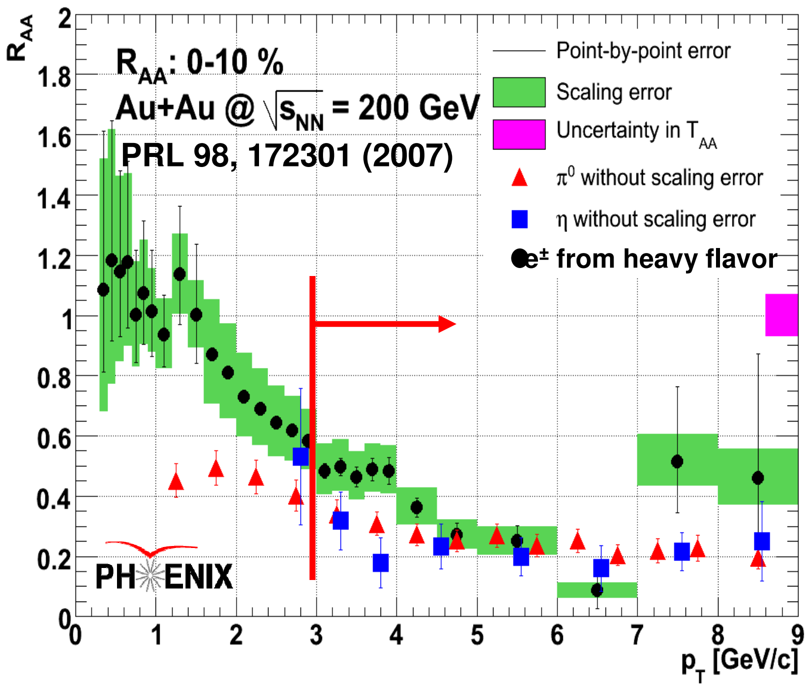
- total cross section

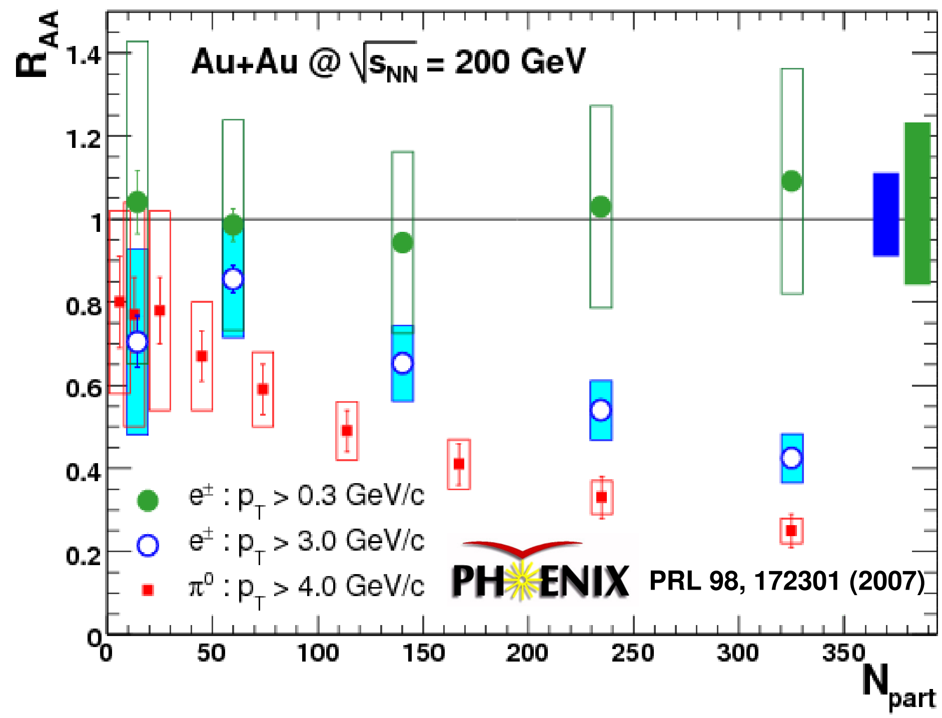
σ_{cc}= 567±57(stat)±224(sys) μb

Spectra from charm and bottom separately



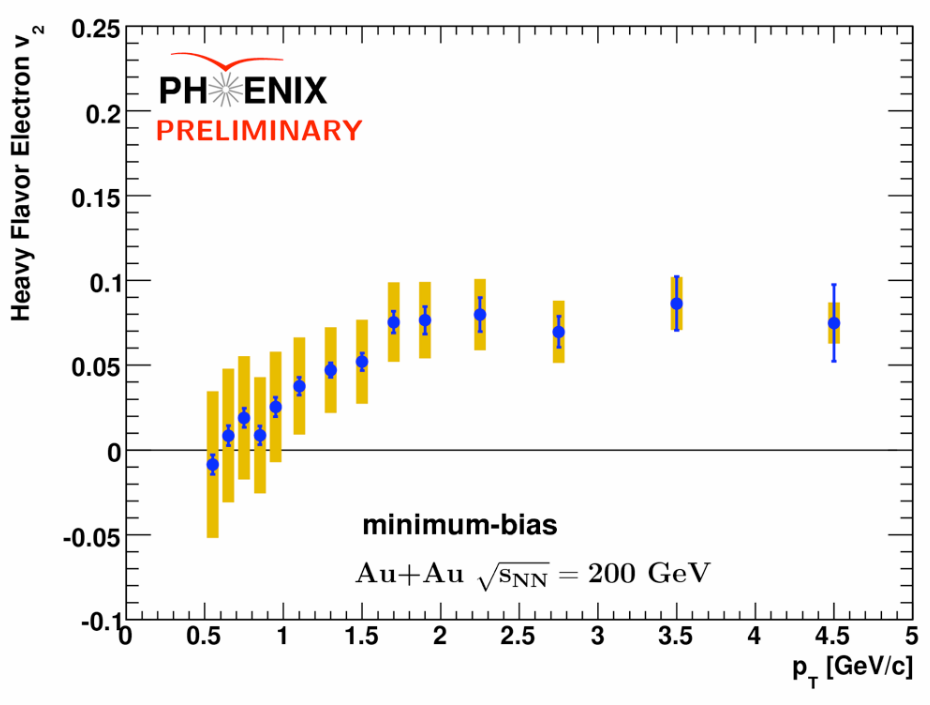
In Au+Au c- and b- quarks are suppressed as light quarks!





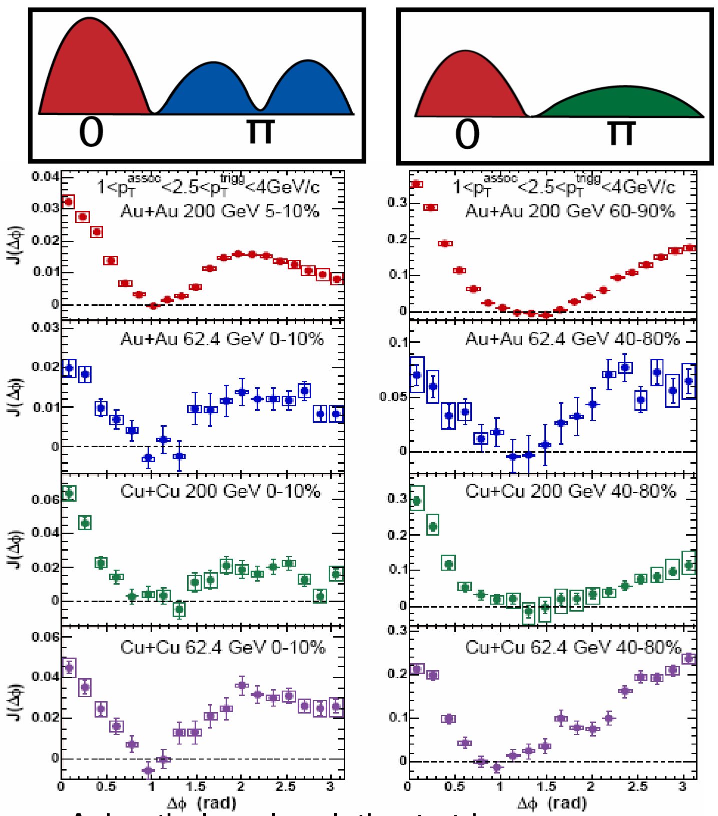
PHENIX : PRL98, 172301 (2007)

c- and b- quarks flow as light quarks



5. Two particle correlation and jet tomography

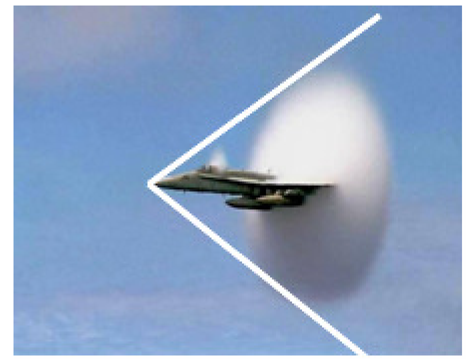
Jet reconstruction difficult in heavy ion collisions
Jet physics can still be studied via two-particle correlations

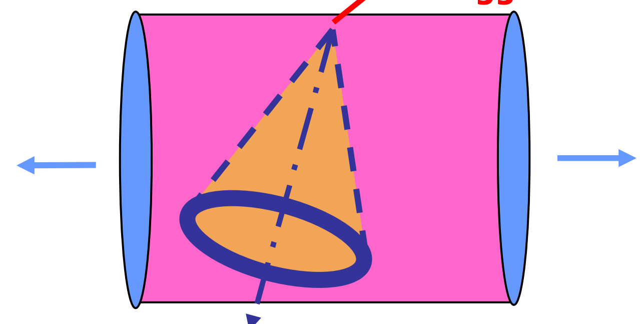


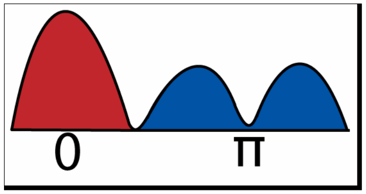
Azimuthal angle relative to trigger

Phys. Rev. Lett. 98, 232302 (2007)

Shock wave, Mach/Cherenkov cone ?

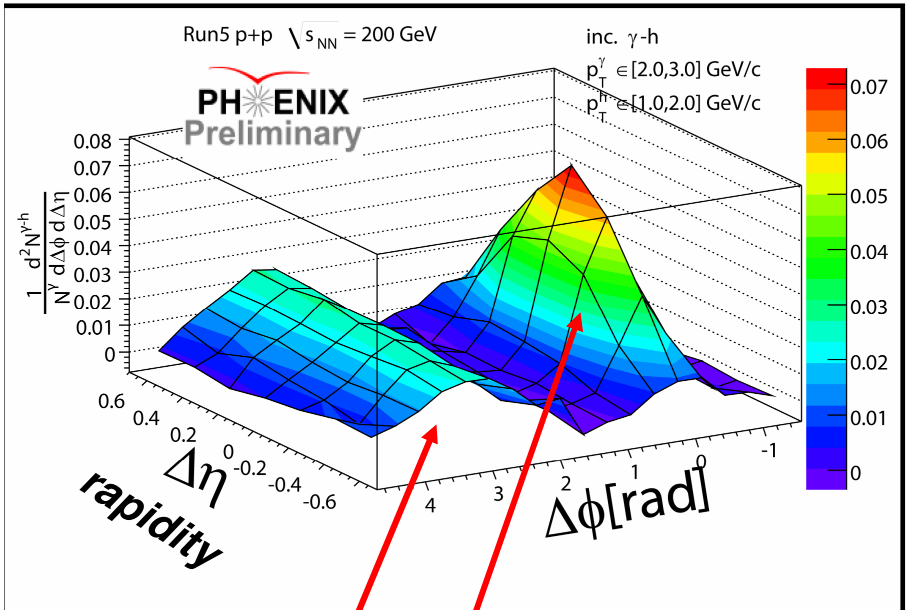




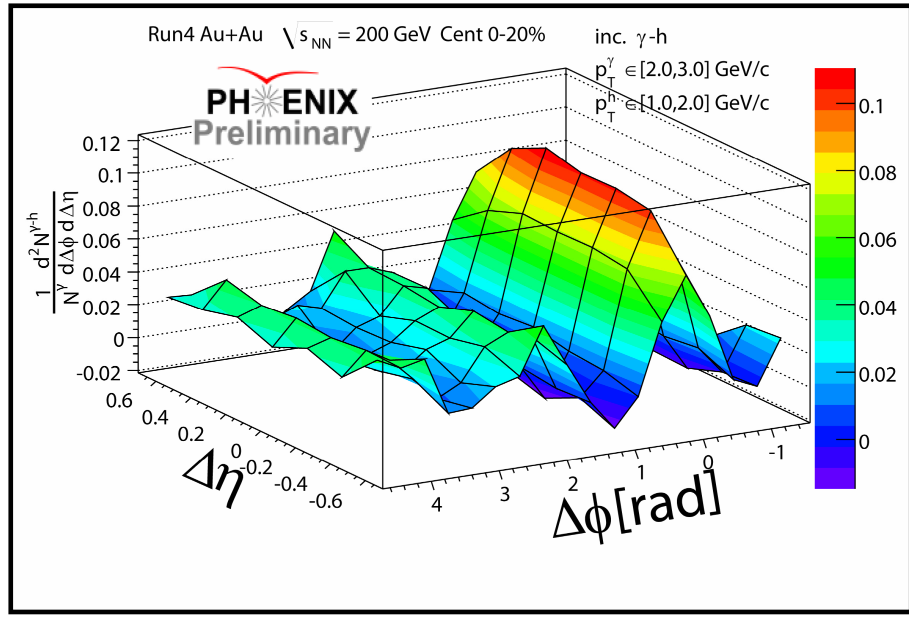


Jets. Medium Response

p+p, peripheral Au+Au



central Au+Au



Away-side Jet

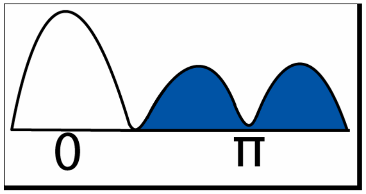
Near-side Jet

Typical

New:

- **Near-side Modification – "Ridge"**
- **Away-side Modification – "Shoulder"**

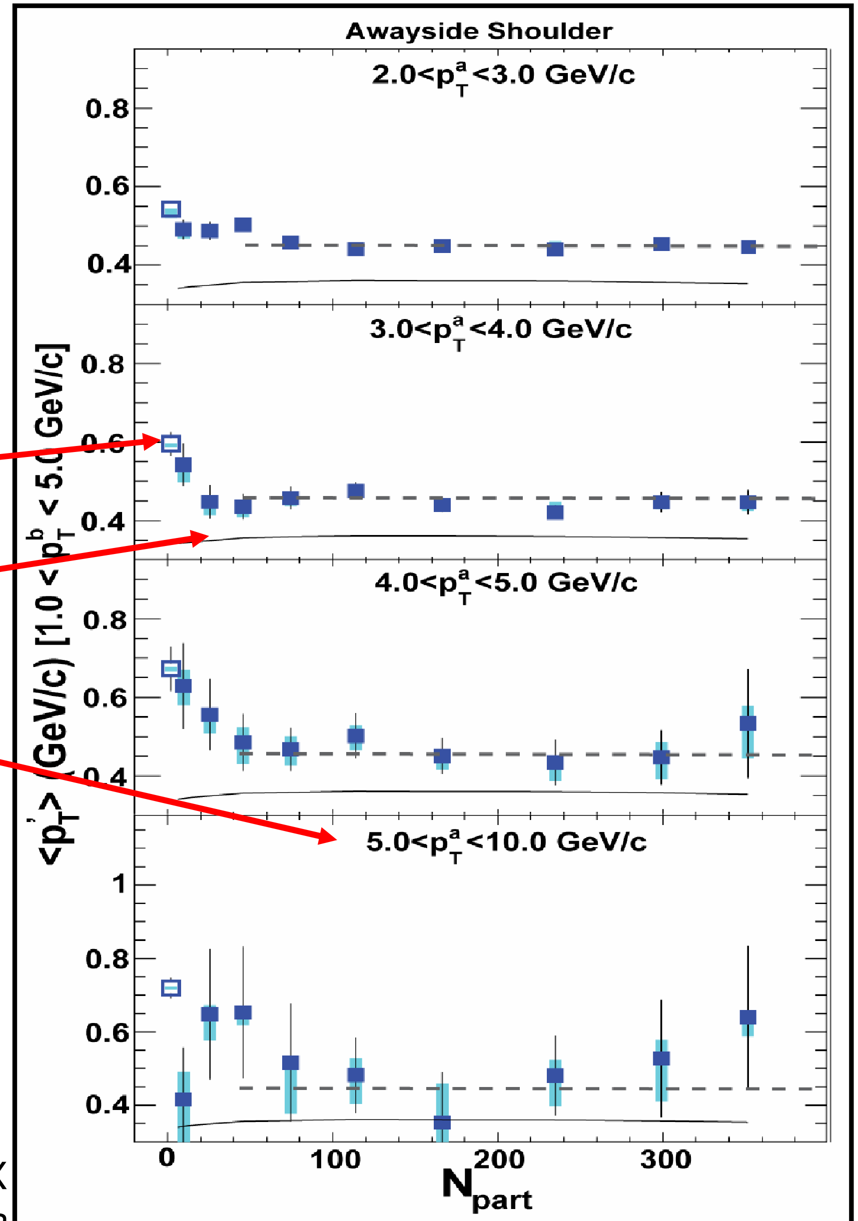
Near-side Ridge theories: Boosted Excess, Backsplash, Local Heating,…
Away-side Shoulder theories: Mach, Jet Survival + Recom, Scattering,…

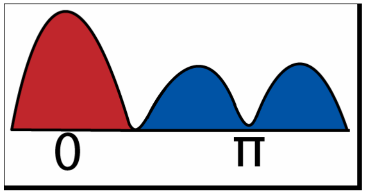


Away-side Shoulder Spectra

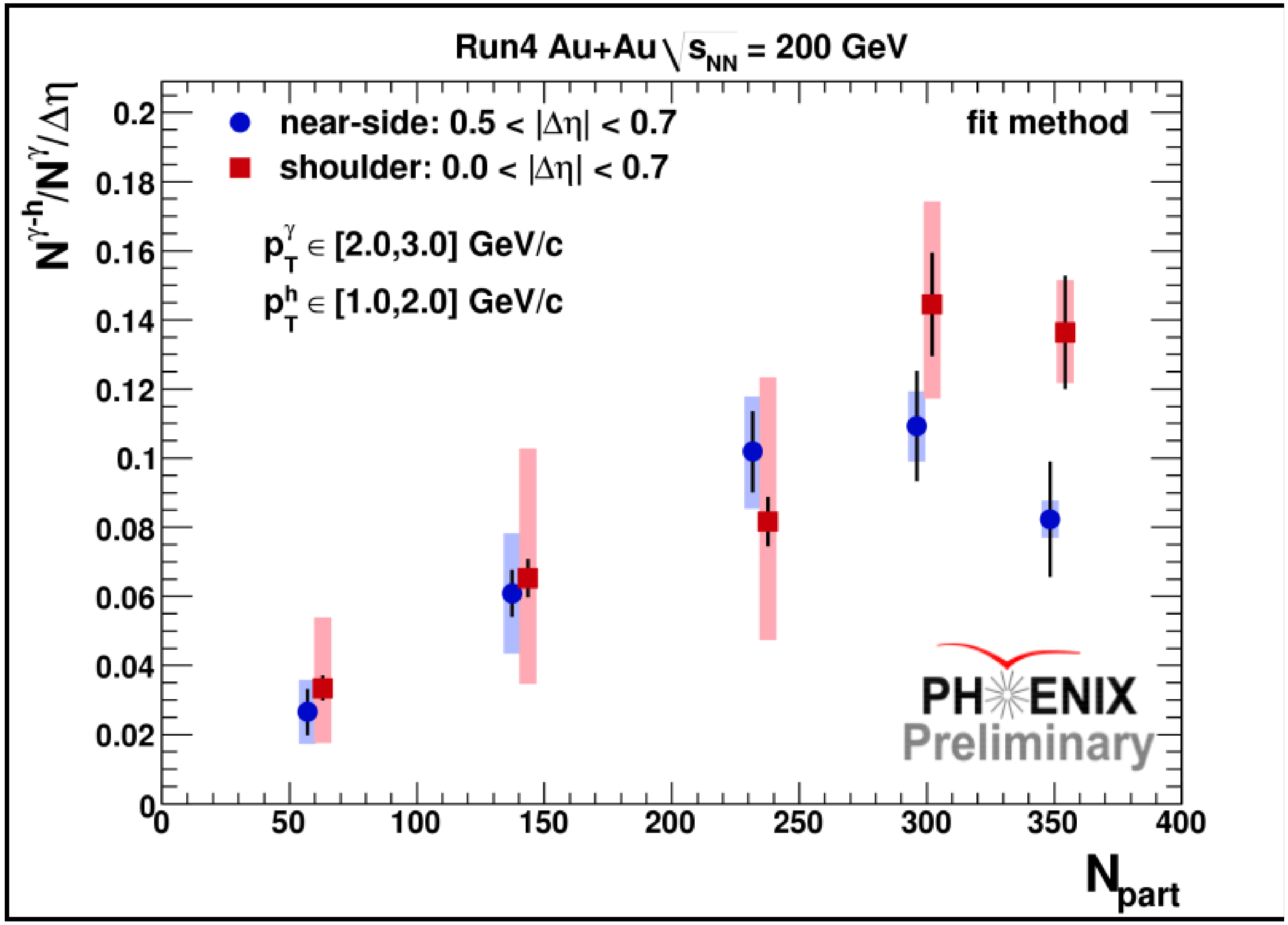
Mid-Central → Central Au-Au:

- Medium response dominates the shoulder bin (>50 N_{part})
- **Softer** than p-p away-side
- Close to **inclusive** spectrum
- Little dependence on **trigger p_T** selection



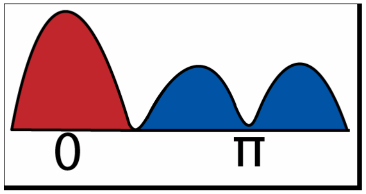


Amplitude- Centrality

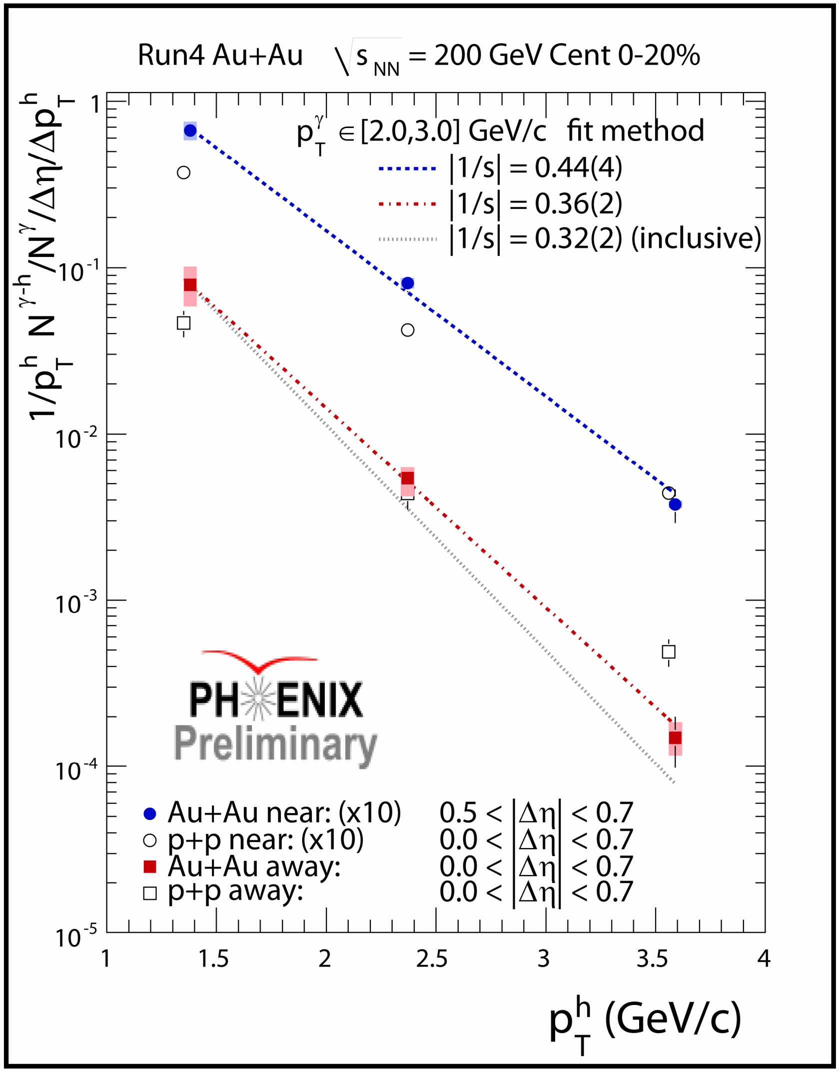


Away-side shoulder and near-side **ridge** share a **common** centrality dependence

- Scale similarity here is largely a factor of p_T selection?



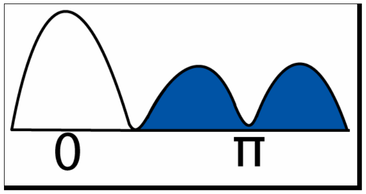
Connections - Spectra



Near-side ridge and away-side shoulder are **both softer** than p-p counterpart jets

- Near-side **ridge** is possibly **harder** than away-side shoulder

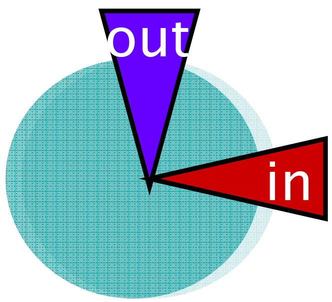
- Away-side shoulder is closest to **inclusive hadron** slope



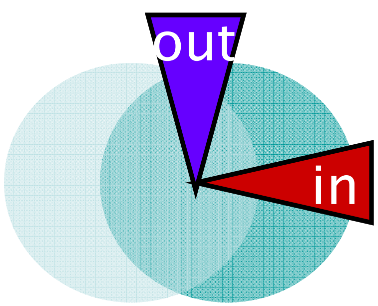
Away-side by Geometry. Preliminary data

Orientation versus Reaction-Plane:

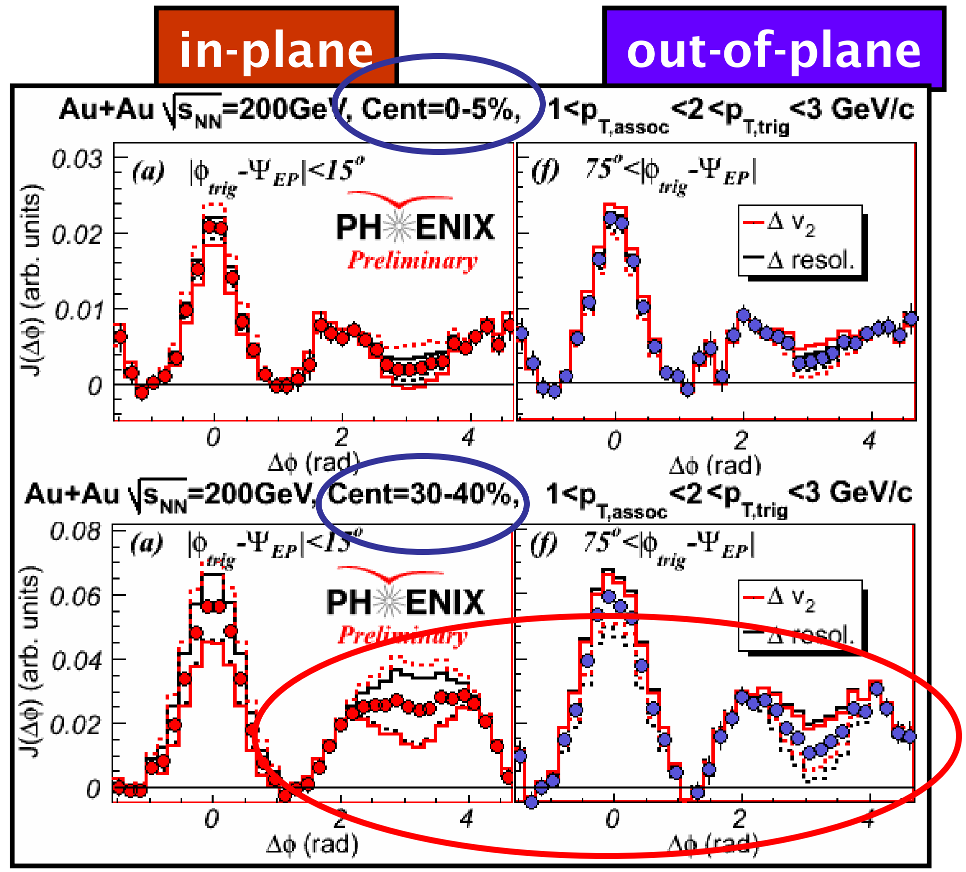
- Reaction-plane resolution sys errors – Black lines (correlate in-out)
- v_2 sys errors – Red lines (anti-correlate in-out)



Cent 0-5%

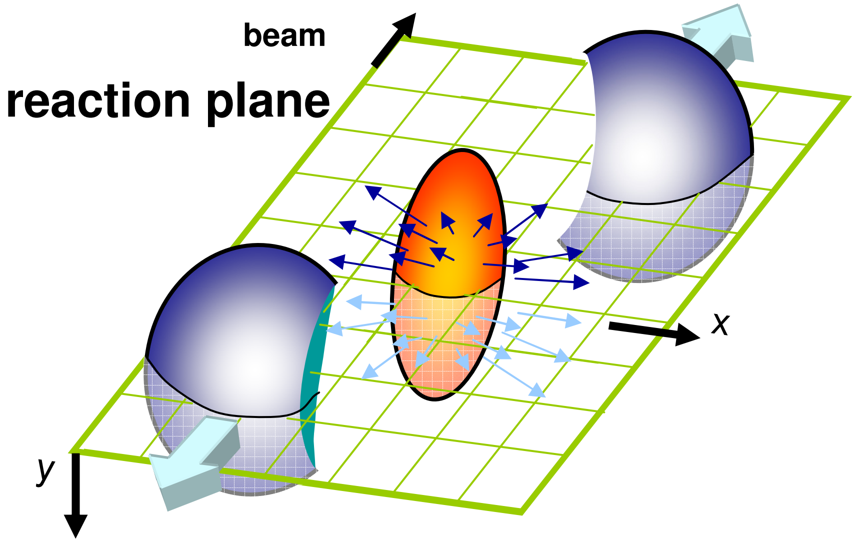


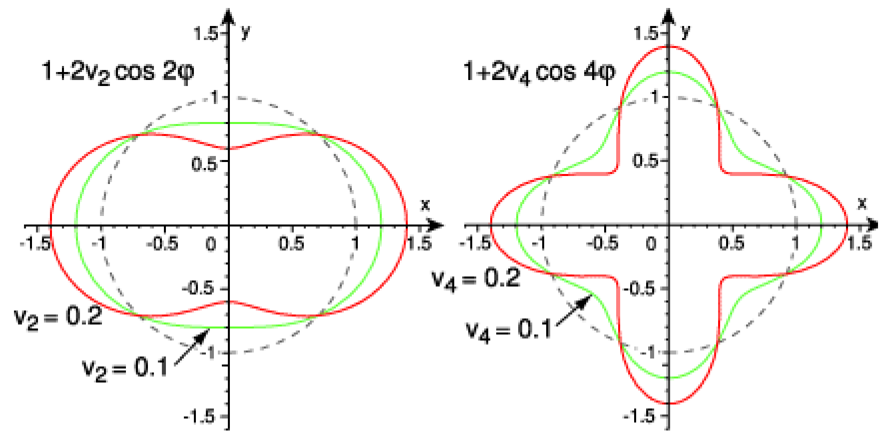
Cent 30-40%



Need more work to quantify

6. Anisotropic flow v_2 and v_4





Peter Kolb, PRC 68, 031902 (2003), nucl-th/0306081

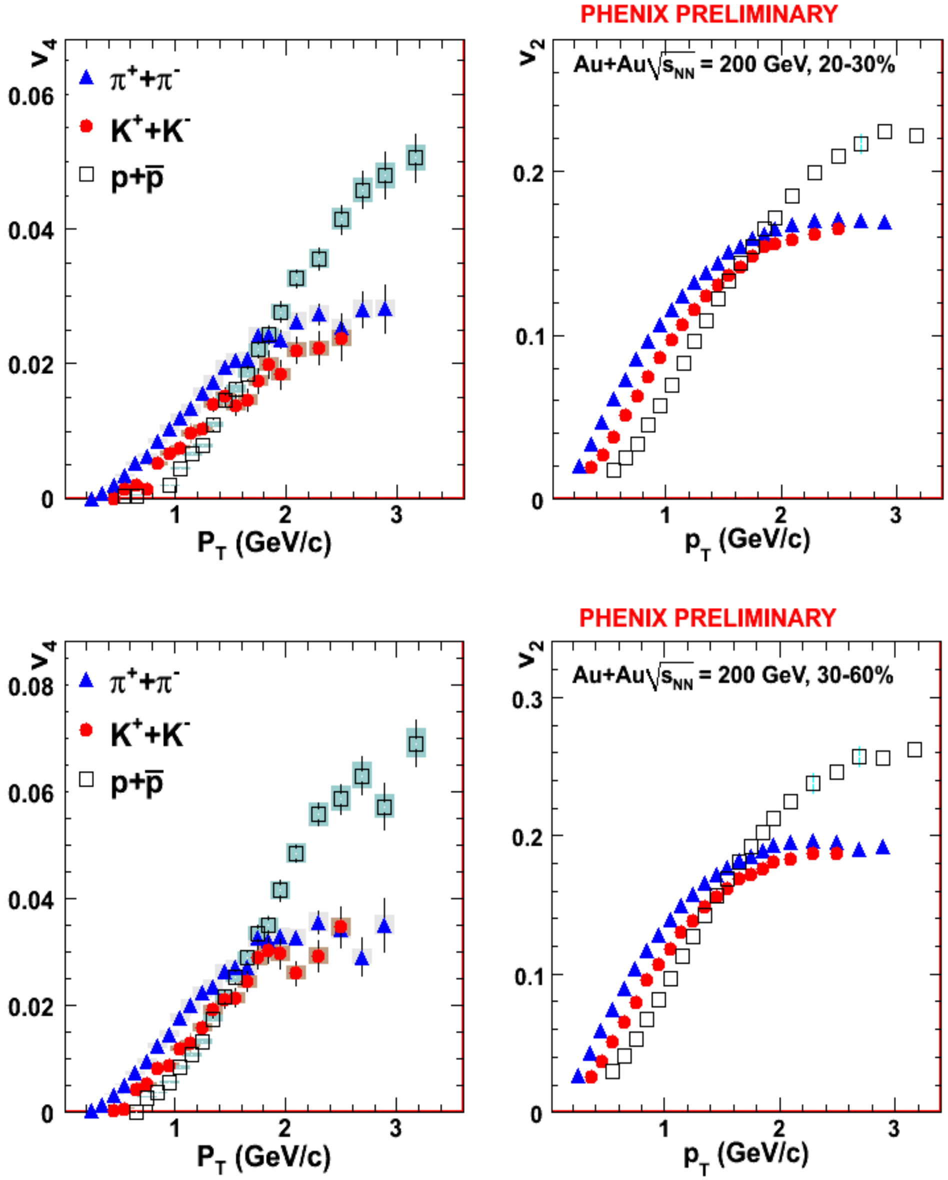
Spatial space asymmetry → momentum space asymmetry

$$E\frac{\mathrm{d}^3N}{\mathrm{d}^3\mathrm{p}} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_T\mathrm{d}p_T\mathrm{d}y}\left(1+2\sum_{n=1}^{\infty}v_n(p_T,y)\cos\left(n\left(\phi-\Psi_r\right)\right)\right)$$

$$v_n = \left\langle\cos\left(n\left(\phi-\Psi_r\right)\right)\right\rangle$$

- **Azimuthal correlation with the reaction plane**
- **Built up in the early stage and self-quenched, therefore supply the early information of matter generated in the collision**

Mass ordering of v_2 and v_4

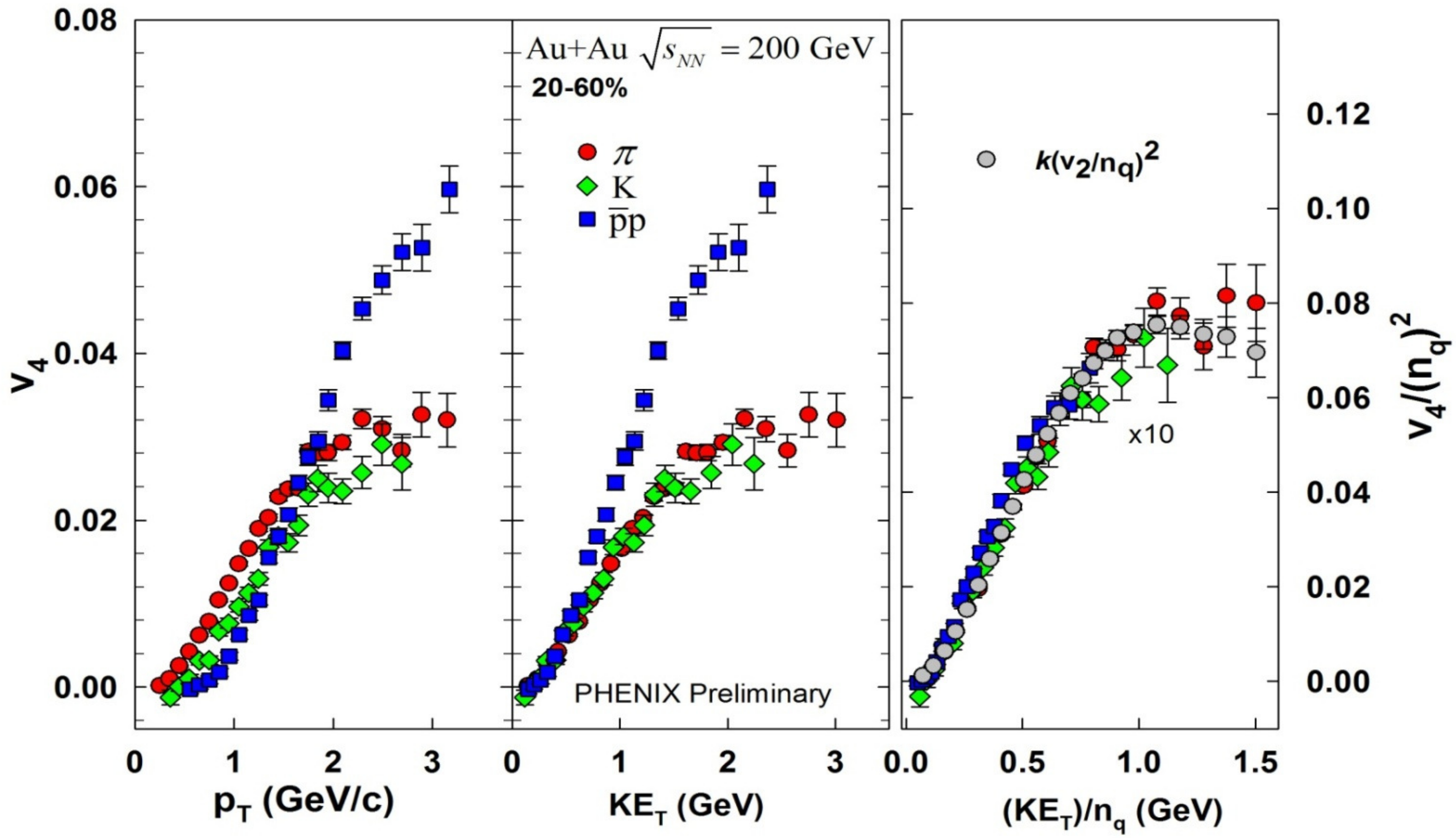


- V_4 has been measured as a function of p_T in different centrality bins for the π, K and p

- Mass ordering has been observed for both v_2 and v_4

Consistent with the hydrodynamics.

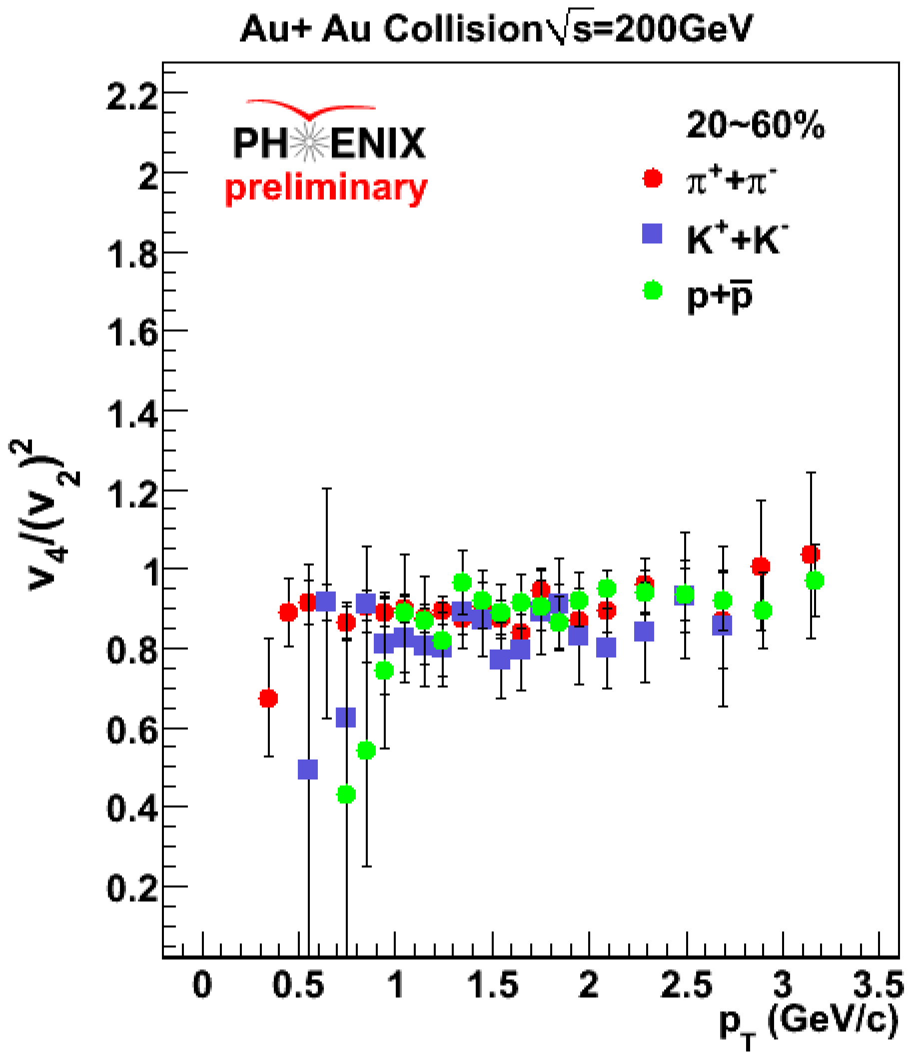
KE_T Scaling of v_4



- The v_4 follows the KE_T scaling well for $KE_T < 1$ GeV

- The number of constituent quark scaling holds for v_4 when $KE_T/nq < 1$ GeV.

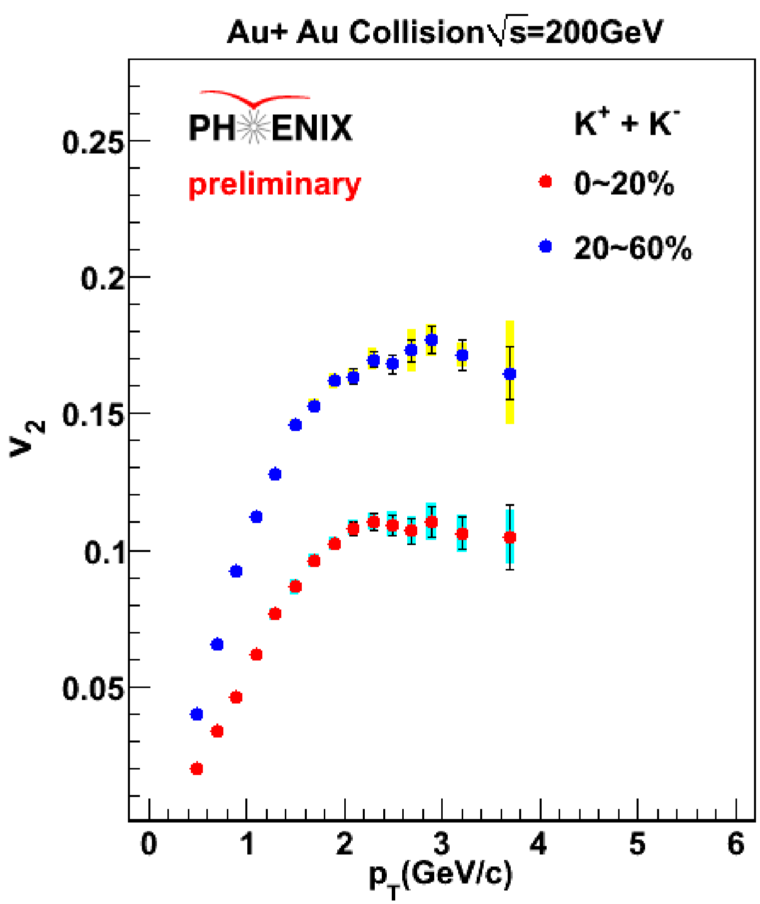
This confirms that matter with partonic degrees of freedom has been generated at RHIC

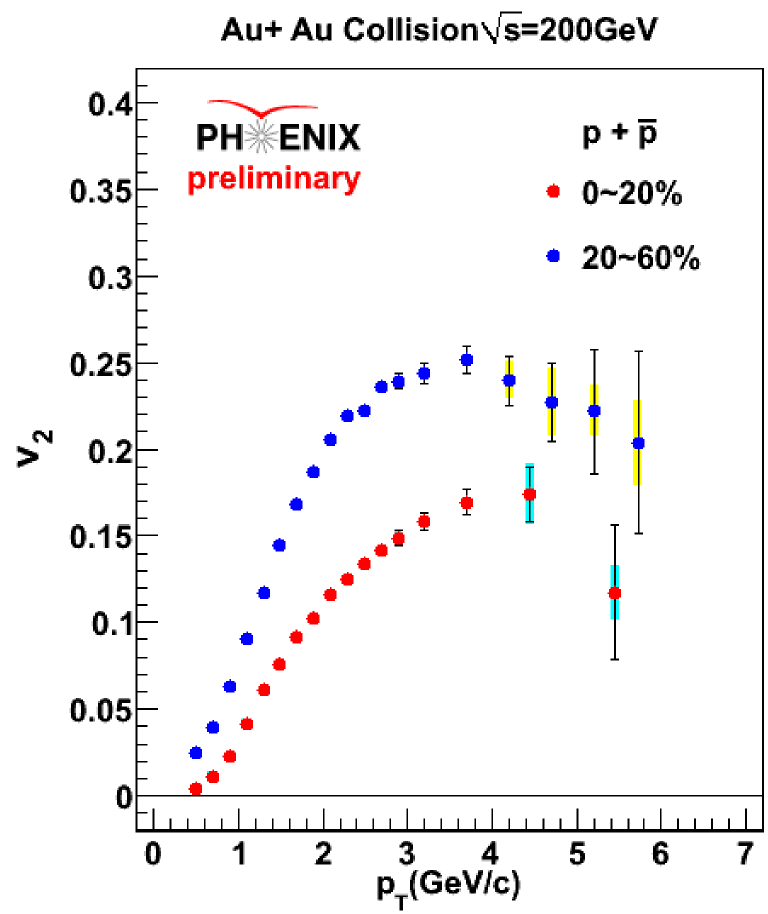


- The ratio of $v_4/(v_2)^2$ is close to 0.9 for the π, K and p

- Mesons and baryons have similar $v_4/(v_2)^2$ ratio

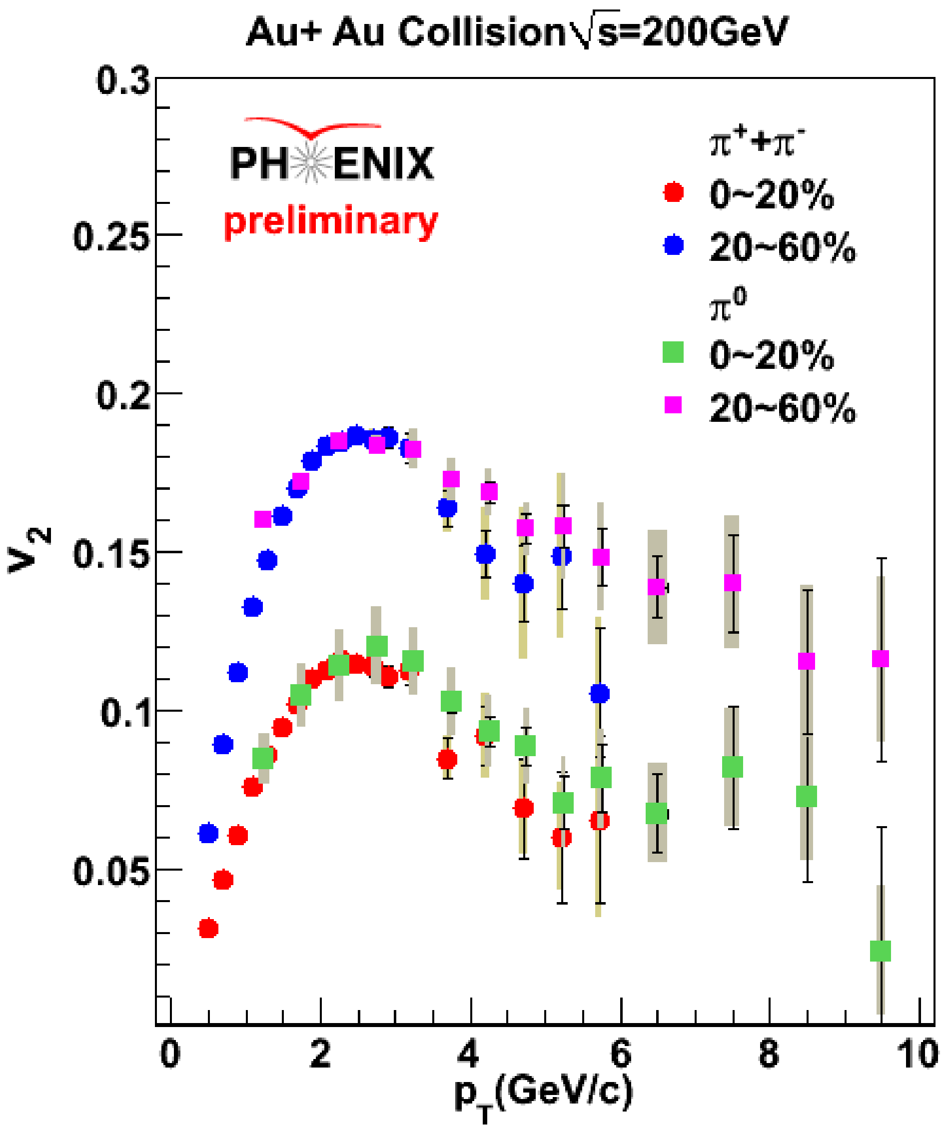
New high pt data on Kaon and Proton v_2





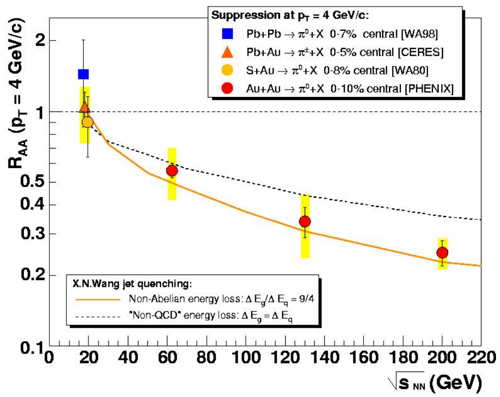
- ➢Kaon v_2 can be measured to 4 GeV/c and protons v_2 can be measured to 6 GeV/c
- ➢Proton v_2 starts to drop at p_T ~ 4 GeV/c

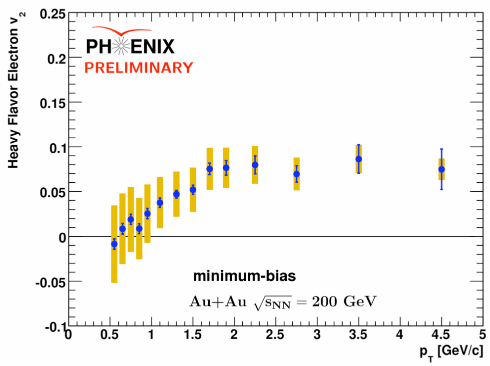
Charged π v_2 at high pt

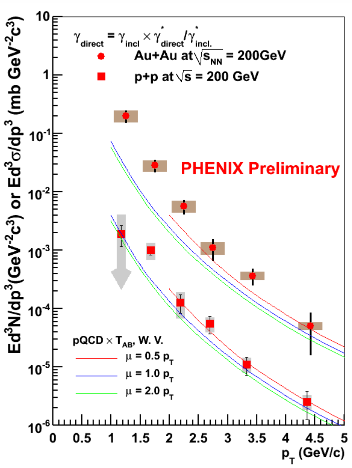


- Charged π v_2 can be measured to 6 GeV/c.
- The results are consistent with π^0 results in the overlap p_T region.
- π v_2 significant at very high pt=6-8 GeV/c!

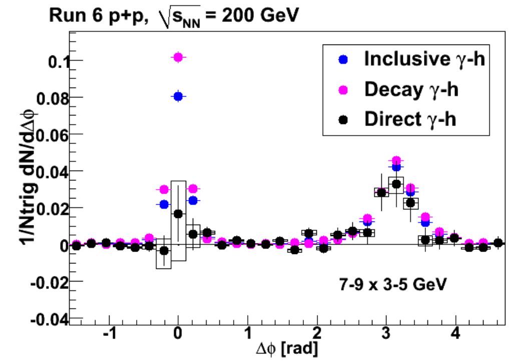
Summary

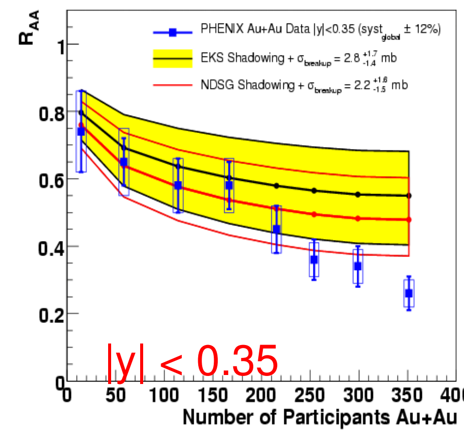


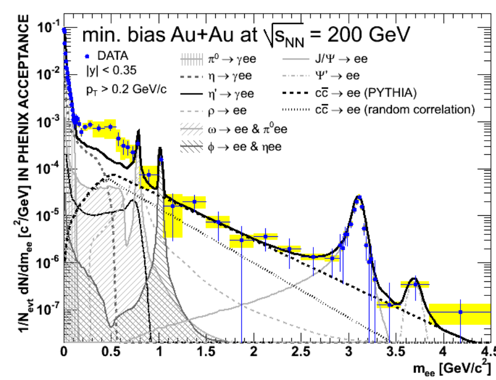




- More precise studies of sQGP matter
  - Systematics of R_{AA}
    - γ-h correlations
  - J/ψ
- Initial T and evolution
  - Low p_T direct γ excess
  - Dilepton excess







Conclusion

PHENIX

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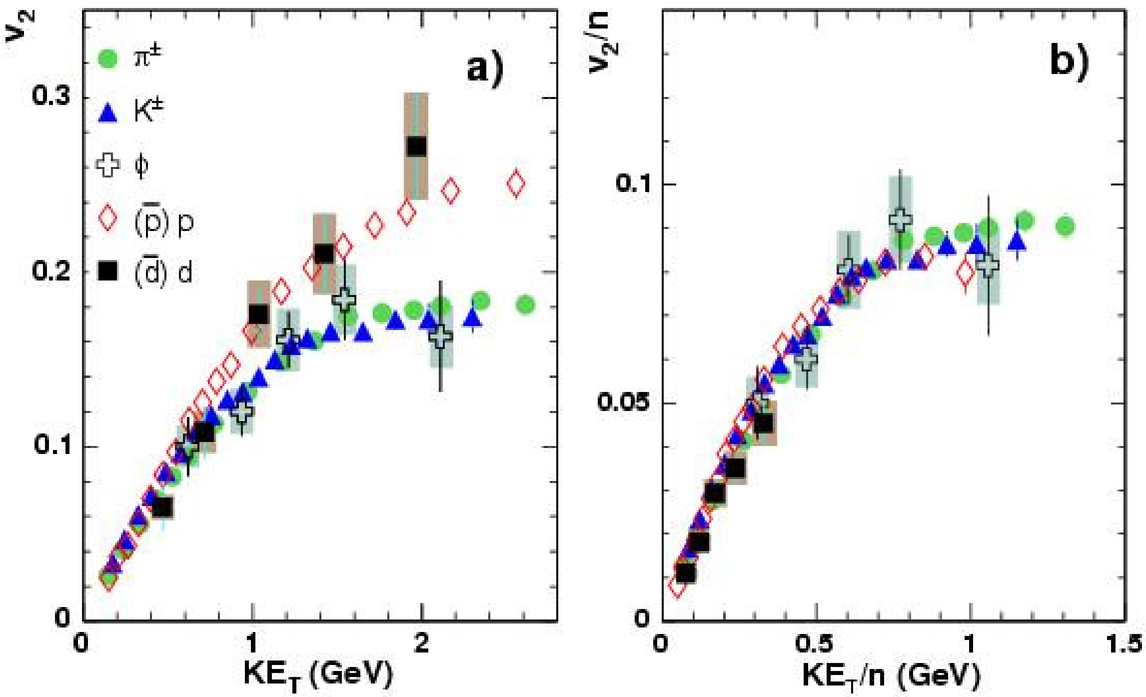
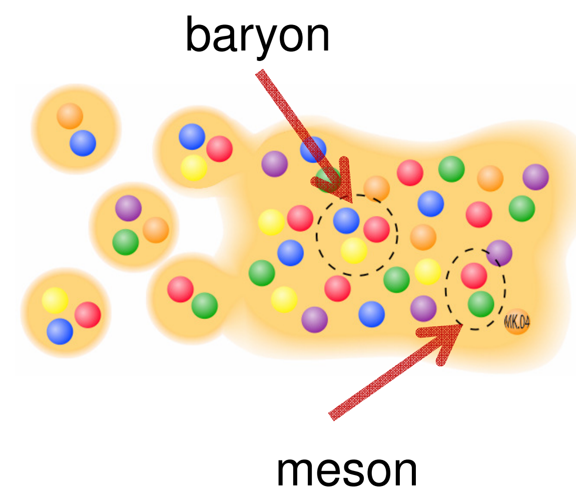
*as of March 2005

backup

Partonic Flow

PHENIX, PRL. 99, 052301 (2007)



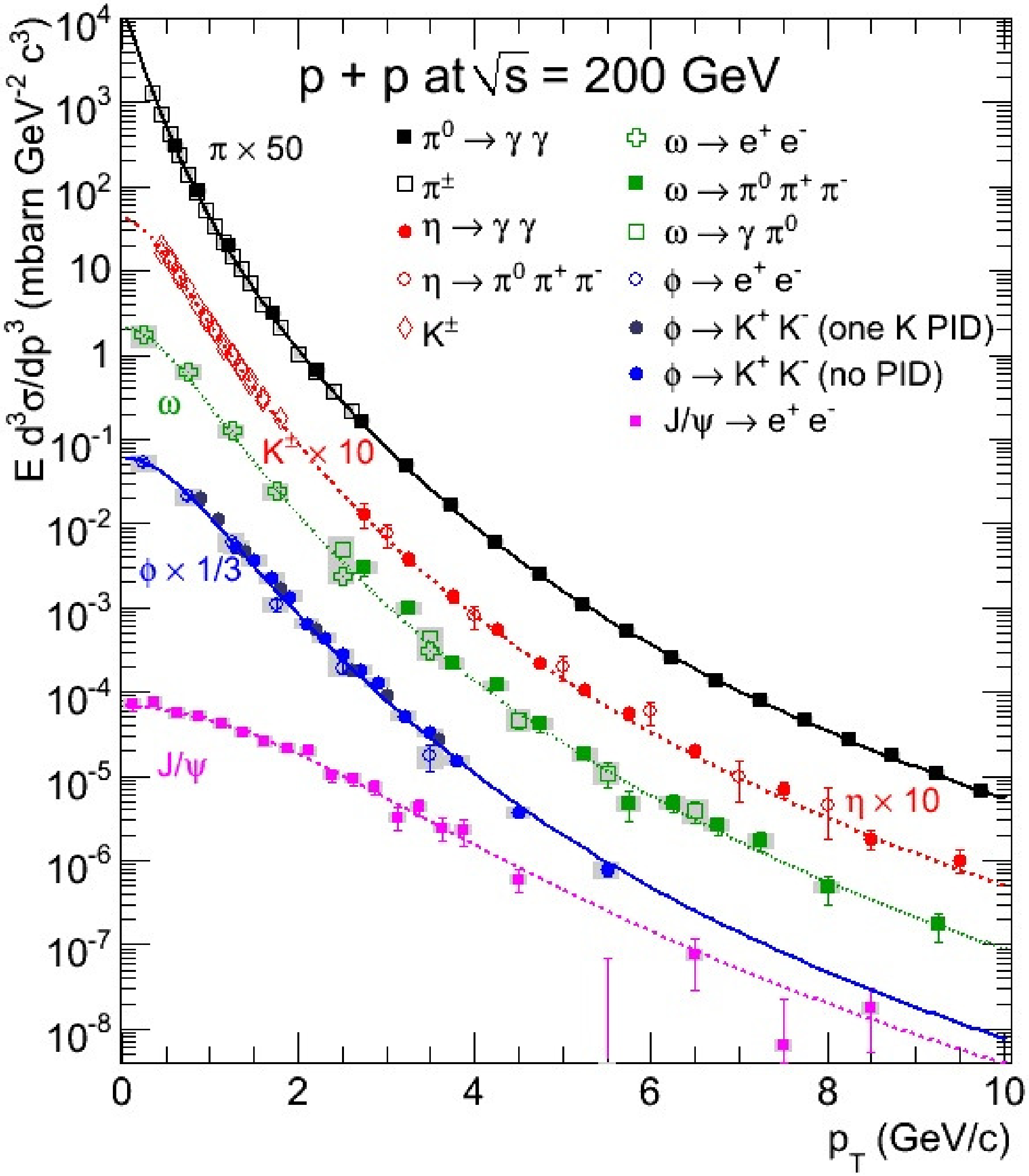


$$KE_T = m_T - m_0$$

Baryon and meson elliptic flow follow the number of constituent quark scaling as a function of transverse kinetic energy KE_T. This indicates that partonic flow builds up at RHIC

◆How about the higher order anisotropic flow such as v_4?

meson p_T spectra - p p

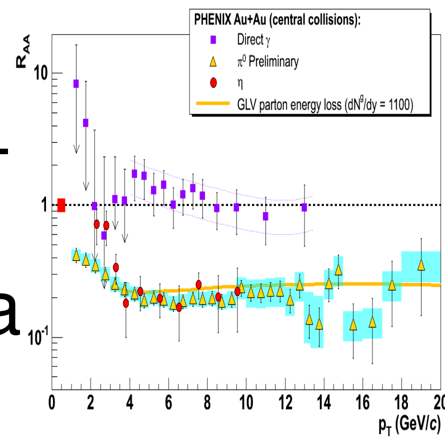


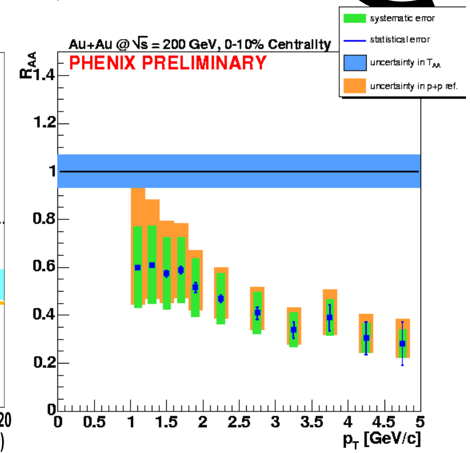
Fit only π^0's with modified Hagedorn function, then apply only m_T scaling to describe other spectra. Absolute scale is the only fit parameter.

Many different detection and analysis methods, PHENIX is a very versatile detector.

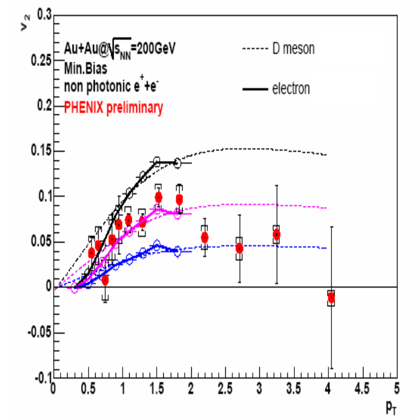
Introduction: sQGP @ RHIC

- QM 2005
  - –strongly inter-acting Quark-Gluon Plasma (sQGP) in HI collisions at RHIC

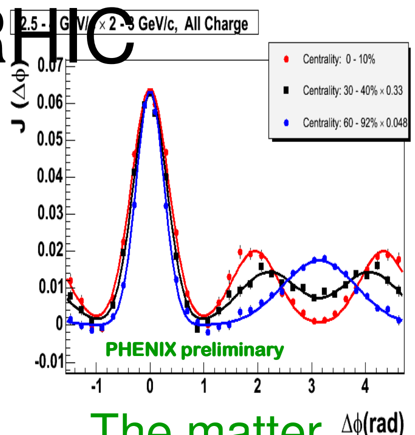




The matter is dense



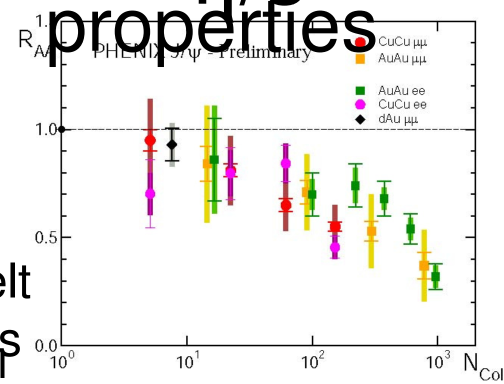
The matter is strongly coupled



The matter modifies jets

- recent hot topic: viscosity/entropy η/s

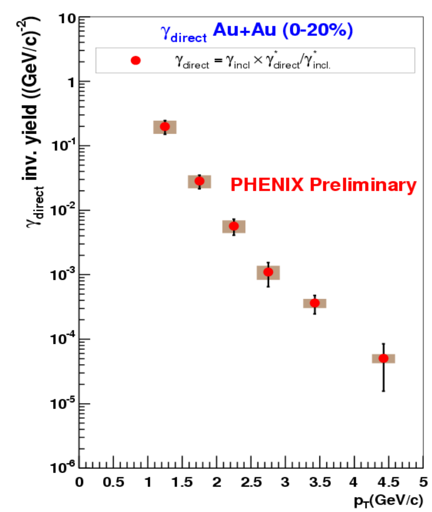
- Next steps
  - –quantify sQGP properties



The matter may melt but regenerate J/ψ's

PHENI

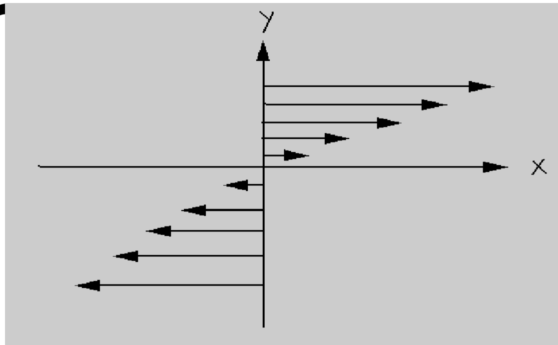
Dubna 2008



The matter is hot

Viscosity Primer

- viscous fluid
  - supports a shear stress
  - viscosity η defined as $\frac{F_x}{A} = -\eta \frac{\partial v_x}{\partial y}$
  - dimensional estimate



$$\eta \approx (\boldsymbol{momentum\ \ density}) \times (\boldsymbol{mean\ \ free\ \ path})$$

$$\approx \boldsymbol{n}\ \overline{\boldsymbol{p}}\ \boldsymbol{mfp} = \boldsymbol{n}\ \overline{\boldsymbol{p}} \frac{1}{\boldsymbol{n}\sigma} = \frac{\overline{\boldsymbol{p}}}{\sigma}$$

large cross sections ↔ small viscosity

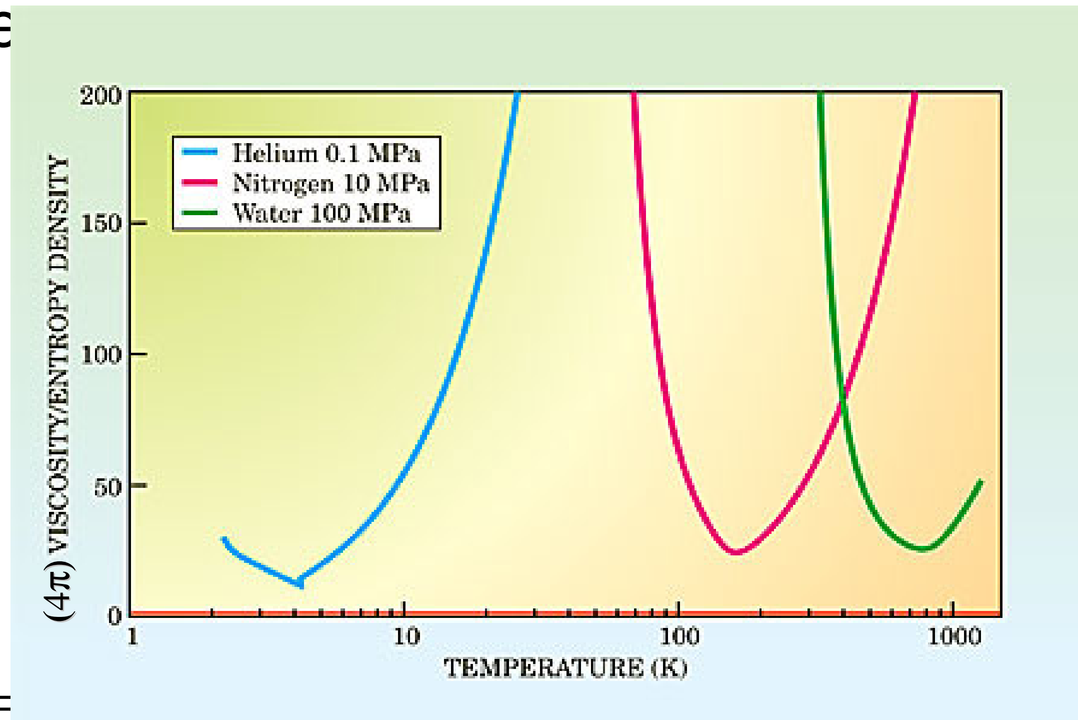
- but how small is “small”?

Viscosity of a “Near Perfect” Fluid

- early hydrodynamic calculations of the medium at RHIC have assumed zero viscosity: $\eta = 0$, i.e. a “perfect fluid”
- conjectured lower quantum limit
  - –derived first in (P. Kovtun, D.T. Son, A.O. Starinets, Phys.Rev.Lett.94:111601, 2005)
  - –motivated by AdS/CFT (Anti de Sitter space / Conformal Field Theo esponde 98)

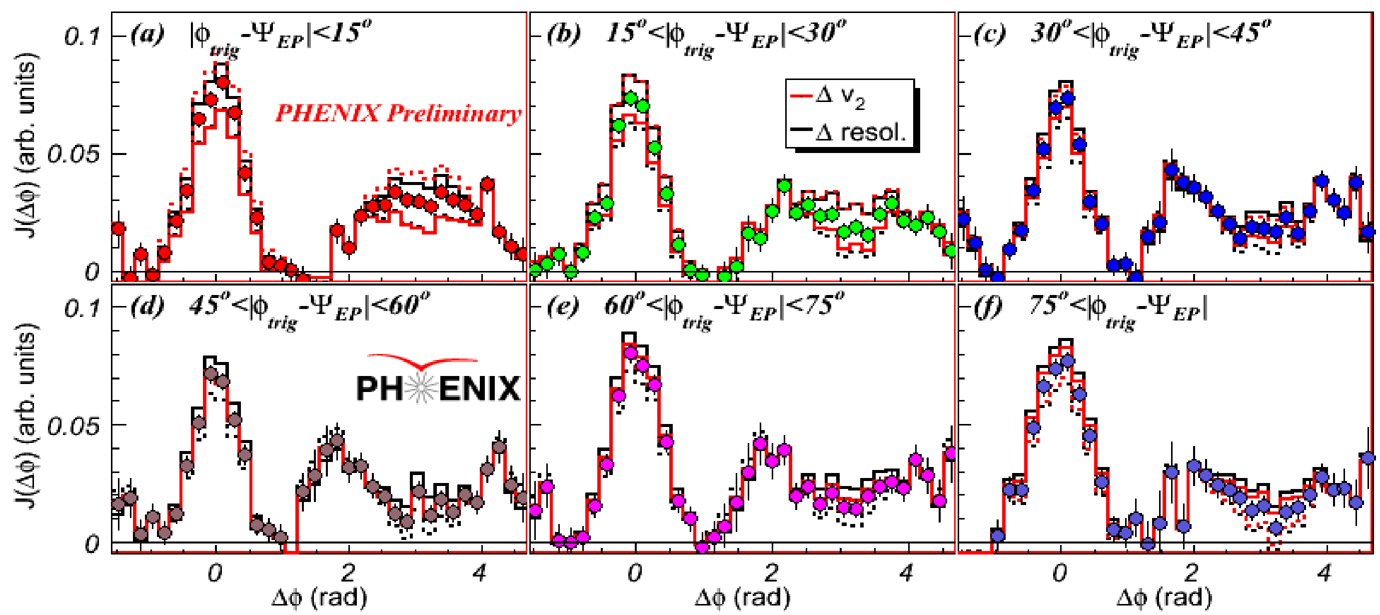
$$\frac{\eta}{s} \geq \frac{\eta}{4\pi}$$

- “ordinary” fluids
  - – water (at normal conditions)
    - $\eta/s \sim 380\ \hbar/4\pi$
  - – helium (at λ point)
    - $\eta/s \sim 9\ \hbar/4\pi$
- “RHIC fluid”?

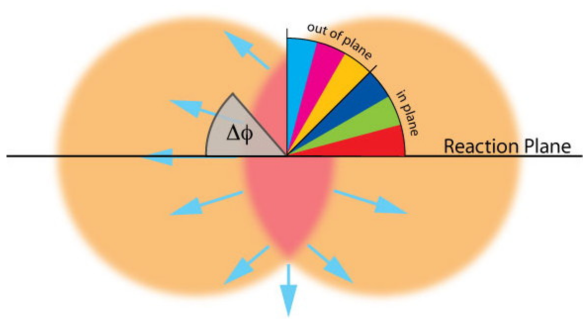


Another handle on path-length: Reaction plane dependence

In-Plane Au+Au $\sqrt{s_{NN}}$=200GeV, Cent=30-40%, $1<p_{T,assoc}<2$ GeV/c, $3<p_{T,trig}<4$ GeV/c



Out-Plane

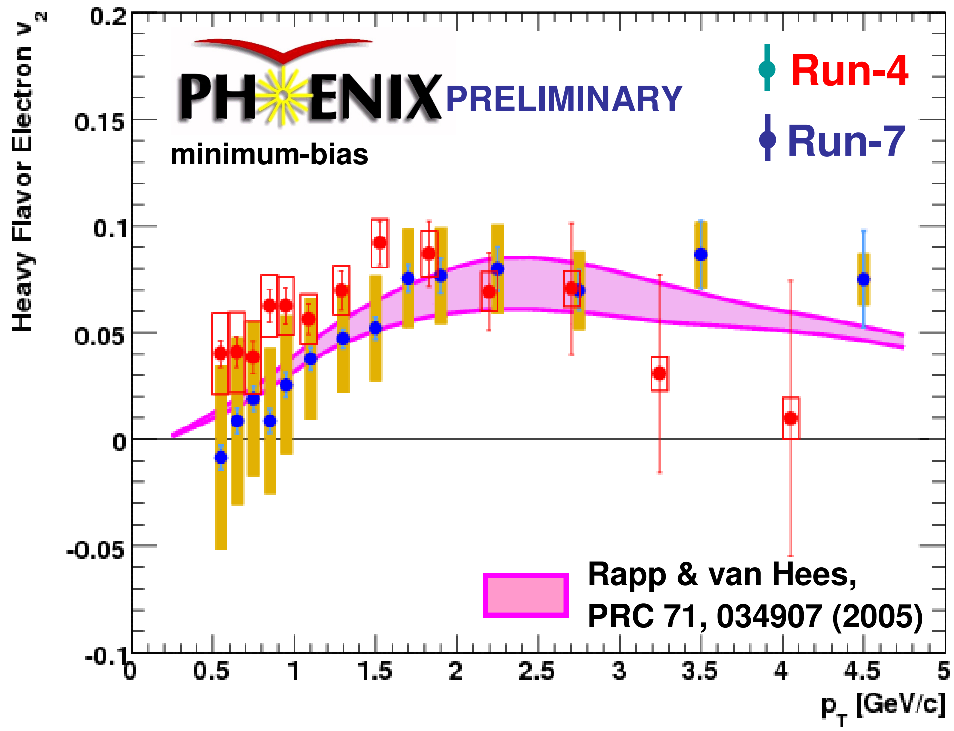


Evolution of "Head Region" is observed.

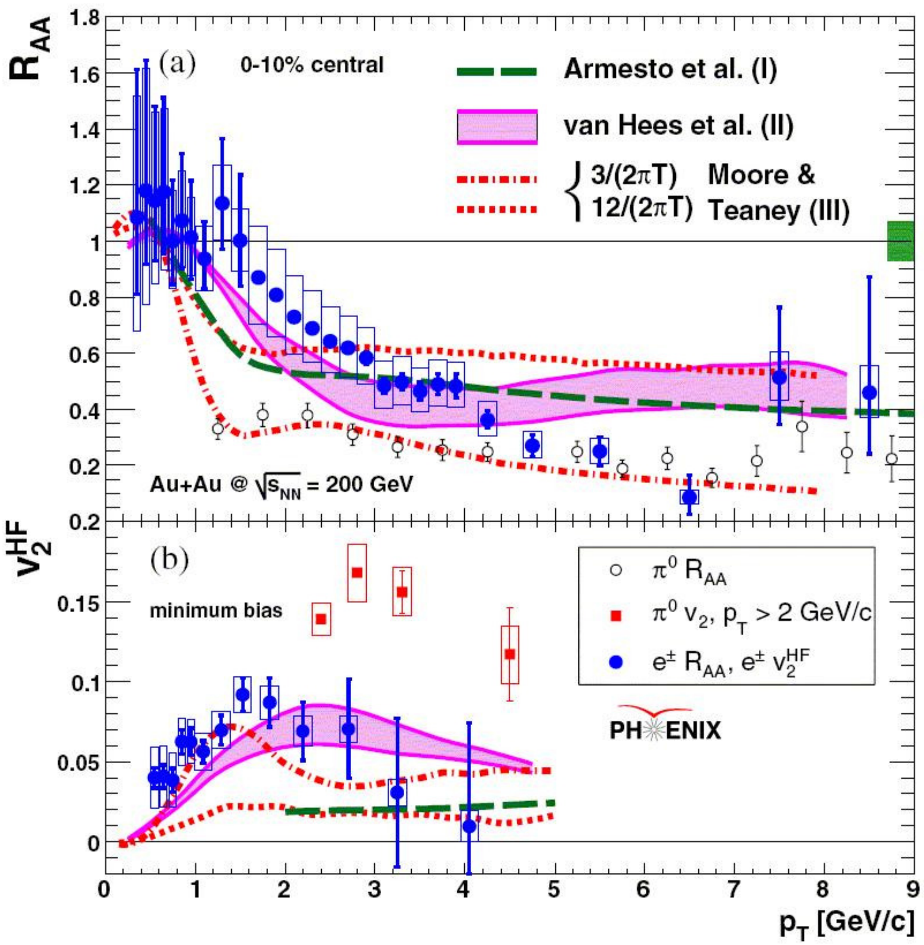
Need more work to quantify that

Measuring η/s

- need observables that are sensitive to shear stress
- damping (flow, fluctuations, <u>heavy quark motion</u>) ~ η/s
- flow
  - R. Lacey et al.: Phys. Rev. Lett. 98:092301, 2007
    - "Has the QCD critical point been signaled by observations at RHIC?"
  - H.-J. Drescher et al.: Phys. Rev. C76:024905, 2007
    - "The Centrality Dependence of Elliptic Flow, the Hydrodynamic Limit, and the Viscosity of Hot QCD"
- fluctuations
  - S. Gavin and M. Abdel-Aziz: Phys. Rev. Lett. 97:162302, 2006
    - "Measuring Shear Viscosity Using Transverse Momentum Correlations in Relativistic Nuclear Collisions"
- heavy quark motion (drag, flow)
  - A. Adare et al. (PHENIX Collaboration): Phys. Rev. Lett. 98:092301, 2007
    - "Energy Loss and Flow of Heavy Quarks in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV"


PHENIX PRELIMINARY
minimum-bias
Run-4
Run-7
Rapp & van Hees,
PRC 71, 034907 (2005)
Heavy Flavor Electron v2
pT [GeV/c]
0.2
0.15
0.1
0.05
0
-0.05
-0.1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

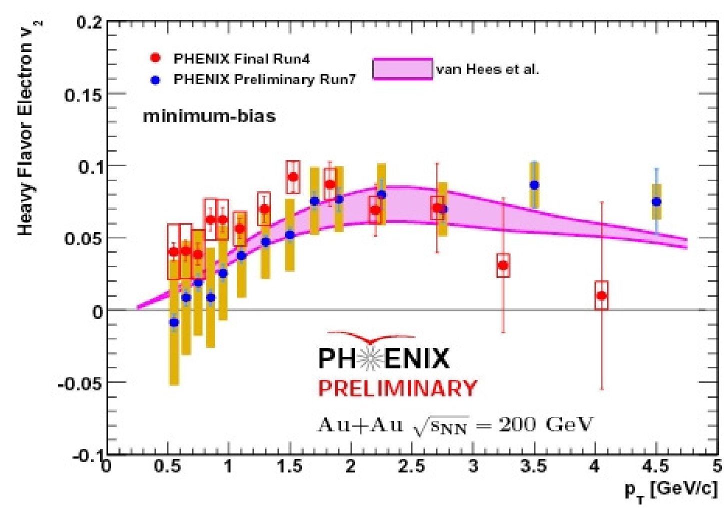
Heavy Flavor via non-photonic Electrons



PHENIX : PRL98, 172301 (2007)

- HF strongly suppressed, Significant v_2
  - Implies high density, small diffusion coefficient
  - Estimate $\eta/s = (1.3\text{-}2)/4\pi$
  - Very close to conjectured limit

Session XIV: Ralf Averbeck

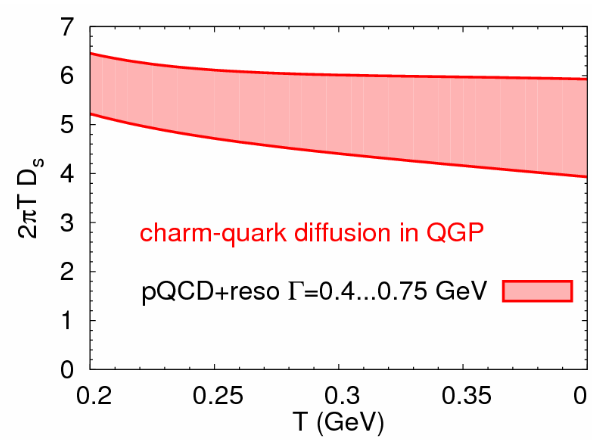


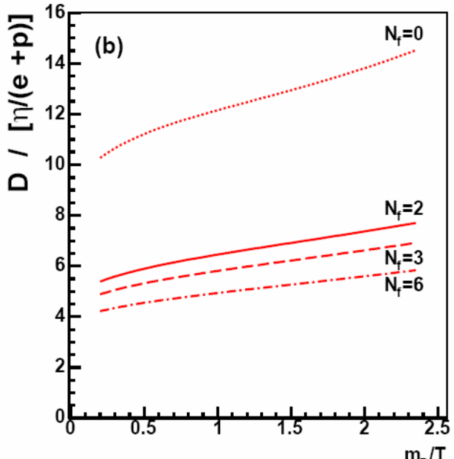
Preliminary Run 7 HF v_2 result:

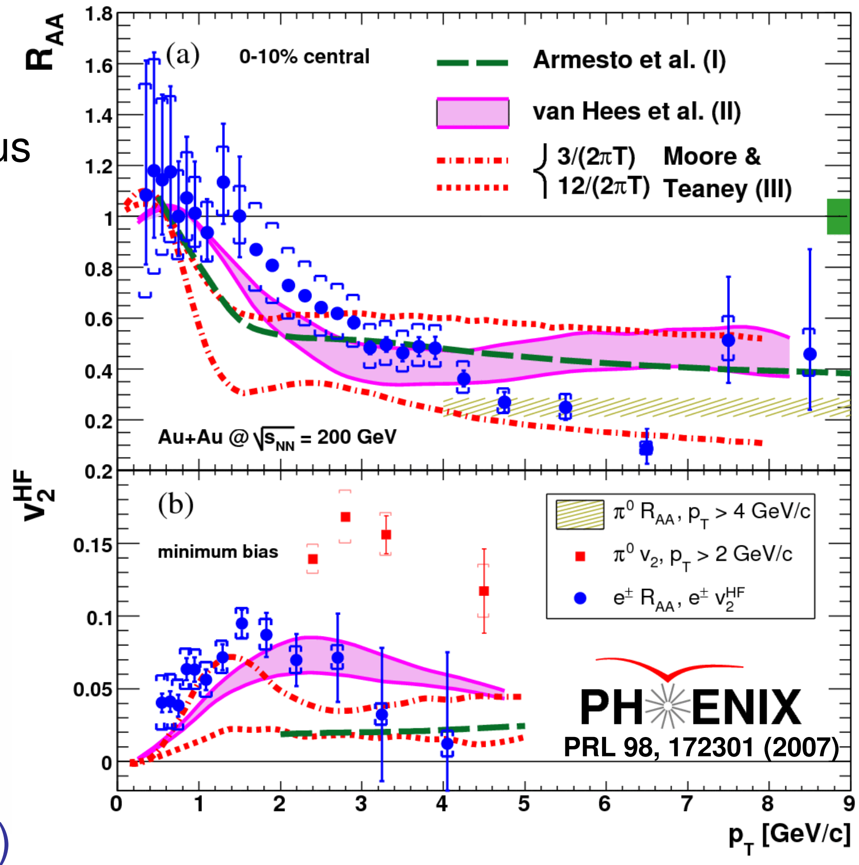
Poster: A.Dion

Estimating η/s from heavy flavor data

- transport models
  - Rapp & van Hees (PRC 71, 034907 (2005))
    - diffusion coefficient required for simultaneous fit of R_{AA} and v_2
      - $D_{HQ} \times 2\pi T \sim 4\text{-}6$







- Moore & Teaney (PRC 71, 064904 (2005))
  - difficulties to describe R_{AA} and v_2 simultaneously
  - calculate perturbatively (and argue that plausible also non-perturbatively)
    - $D_{HQ} / (\eta/(\varepsilon+P)) \sim 6$ (for $N_f = 3$)

$$\eta/s = (1.3\text{-}2.0)/4\pi$$